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16. Abstract

Waste boiler ash (fly ash) is produced by several coal-fired power generating plants in and adjacent to Arizona. A literature search, laboratory test program and analysis of test data indicate that available fly ashes can be advantageously used in lime-fly ash soil mixtures for highway construction. Unconfined, compressive strength, and freeze-thaw and wet-dry durability are included in the development of a mix design procedure aimed at optimizing the proportions of fly ash and lime.

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FINAL REPORT
UTILIZATION OF WASTE BOILER ASH IN HIGHWAY CONSTRUCTION IN ARIZONA

PART II - SOIL STABILIZATION

by

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and

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Submitted to

Arizona Department of Transportation

Highways Division

for

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Sponsored by

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Engineers Testing Laboratories, Inc.
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ABSTRACT

Waste boiler ash (fly ash) is produced by several coal-fired power generating plants in and adjacent to Arizona. A literature search, laboratory test program and analysis of test data indicate that available fly ashes can be advantageously used in lime-fly ash soil mixtures for highway construction. Unconfined compressive strength, and freeze-thaw and wet-dry durability are included in the laboratory test series. Test data are utilized in the development of a mix design procedure aimed at optimizing the proportions of fly ash and lime.

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHO	American Association of State Highway Officials*
ADOT	Arizona Department of Transportation
ASTM	American Society for Testing and Materials
A, B	Constants
Btu	British thermal unit
^oC	Degrees Celsius
cc	Cubic centimeters
CD	Coefficient of determination
CLC	Coefficient of linear correlation
cm	Centimeters
cy	Cubic yard
e	Natural logarithm base (2.718---)
ETL	Engineers Testing Laboratories, Inc.
^oF	Degrees Farenheit
FA	Fly ash
ft, ft^3	Feet, cubic feet
gal.	Gallons U.S.
G_s	Specific Gravity of Solids
gm	Grams
in.	Inch
Kg	Kilogram
KW	Kilowatt
KWH	Kilowatt-hour
lb.	Pound
LL	Liquid Limit
MW	Megawatt
m, m^3	Meter, cubic meter
n	Number of samples
NP	Non-Plastic
psi	Pounds per square inch gauge
pcf	Pounds per Cubic Foot

*Since changed to AASHTO, American Association of State Highway and Transportation Officials.

PI	Plasticity Index
PL	Plastic Limit
s	Standard deviation
σ	Unconfined Compressive strength
V_1	Within-test coefficient of variation
Vol.	Volume
W	Water (usually weight)
X	Independent variable
Y	Dependent variable

CONVERSION FACTORS

To convert from	To	Multiply by
Cubic foot	Cubic meter	2.832×10^{-2}
Cubic inches	Cubic meter	1.639×10^{-5}
Cubic yard	Cubic meter	7.646×10^{-1}
Foot	Meter	3.048×10^{-1}
Gallon (U.S. Liquid)	Cubic Meter	3.785×10^{-3}
Inch	Centimeter	2.540
Pound-force	Kilogram-force	4.536×10^{-1}
Pounds per square inch	Kilograms per square centimeter	7.031×10^{-2}
Sack (U.S. cement)	Kilograms	4.264×10
Tons	Kilograms	9.072×10^{2}
Degrees Farenheit	Degrees Celsius	*

*$^{o}C = (5/9) \times (^{o}F-32)$

PROJECT SUMMARY

Coal-fired steam generating stations in and around Arizona produce millions of tons of waste boiler ash (fly ash) per year, most of which is not utilized in any way. Research has shown fly ash to possess pozzolanic properties thereby making it potentially useful, as a cementitious material, in a variety of construction applications.

The Arizona Department of Transportation, in October, 1974, commissioned Engineers Testing Laboratories, Inc., to undertake a study for the purpose of evaluating potential uses of fly ash in Arizona highway construction. The program was to serve the multiple objectives of developing a low cost construction material, utilizing a previously wasted by-product, and aiding in the conservation of the non-renewable resources, lime and portland cement.

The study was divided into two parts. Part I concerned the utilization of fly ash in portland cement concrete for Arizona highway construction. Included were a literature review, laboratory test program, engineering analysis of data, and the development of a mix design method. The laboratory procedures were directed toward evaluation of compressive strength, flexural strength, freeze-thaw durability and resistance to sulfate attack. Forty-eight mix designs were tested in the strength test series. A number of the mixes were then subjected to the durability and soundness test series. Strengths were determined to be predictable utilizing the proposed mix design method. Fly ashes from the four available sources were found to be beneficial admixtures for portland cement concrete.

An interim report was submitted to the Arizona Department of Transportation in January, 1976. The purpose of the interim report was to present the preliminary fly ash concrete mix design procedure for review prior to the completion of the study.

Part II concerned the utilization of fly ash in soil stabilization for Arizona highway construction. The study program included a literature review, laboratory test series, engineering analysis of data and the development of a mix design procedure for lime-fly ash stabilized soil. Four typical Arizona soils were utilized in the test series, with fly ash from the four principal sources available in Arizona. Laboratory evaluations included combinations of zero to eight percent lime and zero to thirty percent fly ash for each soil type and fly ash source. Unconfined compressive strength, wet-dry durability and freeze-thaw durability were evaluated in the test series. The fly ashes were found beneficial in varying degrees, depending primarily on soil characteristics.

The two year project was completed with the general conclusion that available fly ash could be efficiently utilized in highway construction in Arizona.

CHAPTER 1. INTRODUCTION

The search for more efficient construction materials, and the problem of industrial waste disposal have been combined in the development of uses for waste boiler ash (fly ash) produced by coal-fired power generating stations. Fly ash is a pozzolan, a material with cementitious properties which can be utilized in many construction materials applications. The purpose of this report is to technically evaluate the use of fly ash from local sources, in combination with a particular lime, as a stabilization method with selected Arizona soils.

The study has been conducted through literature search, laboratory testing and engineering analysis of the data developed. In carrying out the literature search, an effort was made to review all English language literature pertinent to the subject, with no regard for geographic origin. The laboratory studies utilized fly ash from the four principal sources which were found to be available to the Arizona construction market. Lime was obtained from a single source, thereby making fly ash source and soil type the principal variables in the test program. Test series were designed to evaluate unconfined compressive strength, resistance to wetting and drying and resistance to deterioration from freezing and thawing.

Review of the literature and engineering analysis of the test data culminated in the development of a mix design procedure for lime-fly ash soil mixtures, based on unconfined compressive strength and economic optimization of lime and fly ash proportions.

The results of the literature survey are presented in the chapter entitled Literature Review. Comment on the literature has been categorized by subject, for convenience (i.e., compressive strength, field performance, mix design). References have also been organized by subject in the Subject Index to References immediately following the References near the end of the report.

Laboratory test procedures and results are presented in the middle chapters of the report along with analyses of the data. The principal topics, strength and durability, are the subjects of separate chapters.

The mix design chapter includes an introductory evaluation of methods presently in use and a final section on evaluation of the proposed mix design method. The middle sections of the chapter can be independently used as a working outline for the proposed mix design method.

Information relative to the production and quality of fly ash sources used in the study has been placed in an appendix, since the evaluation of time variation in fly ash quality was not a principal objective of the program.

CHAPTER 2. LITERATURE REVIEW

2.1 Historical Development

2.1.1. Ancient Applications

In the third century B.C., the Roman builders made a significant discovery. At the port of Pozzvoli, near Vesuvius, were deposits of sandy volcanic ash which, when added to lime and water, made a cement which dried to rocklike hardness and even hardened under water. They called this material "pulvis puteolanus". By mixing this cement with sand and gravel they made concrete. First use of this material was as a filler between veneer finishes since durability to exposure was questioned. Nonetheless, some of the more daring builders of that time began using the material in exposed construction and surprisingly found the durability satisfactory. Thus, the material use spread widely. Structures, the Colosseum and the Basilica of Constantine, and distribution systems, the Clocaca Maxima and the Aquaducts, were just a few of the facilities built utilizing this new material. Many of these structures still exist today and attest to the durability of the new found material.

The Roman method of making cement, combining lime and pulverized volcanic ash, was essentially the only method employed until 1824, although numerous processes had been attempted. At that time, the first successful process of artifically combining and calcifying clay and limestone to form a hydraulic cement was realized. With the development of a manufacturing process to produce high quality hydraulic cement, known today as portland cement, the use of natural cementing agents declined rapidly.

The natural material employed by the Romans is classified today as a pozzolan. A pozzolan is defined as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Pozzolans may be either natural materials or synthetics which consist of glassy materials produced by rapid cooling of molten silicate mixtures. Fly ash, the finely divided residue that results from the combustion of ground or powdered coal that is subsequently collected from the flue gases, is an example of a synthetic pozzolan. Fossil fuel power plants are the major producers of the material.

2.1.2. Fly Ash in Soil Stabilization and Highway Construction

Following World War II, the enormous expansion in the construction of the inter-state highway system revealed a critical shortage of satisfactory road-making aggregate within economic haul distances of the construction sites. This shortage and the early post-war success of the Texas Highway Department in the widespread use of lime to stabilize roads prompted an intensive program of laboratory and field testing by a number of state and federal government institutions (35).*

Lime-fly ash soil stabilization was developed partially as a result of the poor pozzolanic quality of natural soils in many regions and the relative ineffectiveness of lime stabilization. Probably the most significant early post-war research relating

*Numbers in parenthesis in this section and throughout the report correspond to source title listed in the Reference section.

specifically to lime-fly ash soil stabilization was performed by Minnick and Miller around 1950. These researchers concluded that the addition of lime and fly ash to a soil generally increased the strength and durability of that soil appreciably (35, 82).

Since that time extensive research has been undertaken regarding the use of fly ash and lime in soil stabilization. Most researchers have concluded that lime-fly ash addition to soils in the correct proportions can greatly increase the strength and durability of a soil while at the same time providing an ecologically and economically preferable mix.

One of the best testimonials to the performance of lime-fly ash materials is the growth in their use. The first lime-fly ash pavements were placed in the Philadelphia area in the late 1940's. Growth in the use of this type of material was slow for the first several years until the profession developed a backlog of engineering data and confidence in the material. Since the mid to late 1950's, growth in the use of lime-fly ash pavement materials has been increasing at an increasing rate (10).

2.1.3. Specifications for Fly Ash

As will be discussed later, fly ash varies from one power plant to another and from time to time in a given plant. Due to this variability, specifications have been established to use as a guide for assessing the general characteristics of the fly ash. The first specifications issued in 1954 by the American Society for Testing and Materials applied only to the use of fly ash as an admixture to concrete. Numerous modifications were later adopted and in 1960 specifications were issued relative to the acceptance of fly ash as a pozzolan. The current ASTM specification, Designation: C618-73, segregated all pozzolans into three classes; raw or calcined natural pozzolans, Class N; fly ash, Class F; and others, Class S. This specification is applicable for both the chemical and physical requirements of the pozzolanic material. The current ASTM specification forms the basis for all standard and/or special provision specifications issued by the state highway agencies. Table 2-1 contains the current ASTM specification for fly ash and the specificiations issued by some of the state highway agencies and other public agencies. For the state specifications, entries have been designated only for those requirements which are in variance with the ASTM specification. In general, the state's specifications are more restrictive than the ASTM, particularly in regard to the loss on ignition requirements.

It is noted that a modification of ASTM Designation: C618-73 is presently under review by ASTM Committee C-9 and is to be voted upon for possible adoption. The review specification contains two classes for fly ash as a pozzolanic material: Class F, fly ash derived from anthracite or bituminous coal; and Class C, fly ash derived from lignite or subbituminous coal. The review specification for Class F fly ash is the same as the current specification given in Table 2-1 with the following exceptions:

a) Blaine fineness requirement has been eliminated;
b) Pozzolanic Activity Index with portland cement has been lowered to 75% minimum;
c) Autoclave soundness has been increased to 0.8%

TABLE 2.1 Specifications for Fly Ash

Property	ASTM C-618 Class F (6)	Std. Ala.	(1) S.P. Fla.	S.P. Ga.	S.P. Ind.	S.P. Ky.	S.P. Neb.	S.P. W.Va.	S.P. Mich.	S.P. Wisc.	Std. Minn.	(3) N. Dak. F1	N. Dak. F2	Corps of Engrs.	Federal
pH min.		7.0		7.0											
SiO_2 %				40.0											
Al_2O_3 %		15.0		15.0											
Fe_2O_3 %															
Sum of Oxides % min.	70.0										45.0	70.0	5.0	70.0	75.0
MgO % max.		5.0		3.0								5.0		5.0	5.0
SO_3 % max.	5.0	3.0		3.0							12.0		7.0	4.0	4.0
Moisture % max.	3.0	1.0												3.0	3.0
LOI % max.	12.0	6.0	6.0	6.0	8.0	6.0	6.0	6.0	4.0	5.0	5.0		6.0	6.0	6.0
Available Alk. as Na_2O % max.	1.5 (2)	1.5									3.0		2.5	1.5	2.0
CaO % max.											35.0		35.0		
Free Carbon % max.							3.0								
Fineness cm^2/cm^3 min.	6500			3000 (4)										6500	6500
Retained #325 % max.	34	25		20.0					10.0		30.0	20.0	30.0	(7) N.S.	N.S.
Multiple Factor	255.0											150	150	N.S.	N.S.
Pozz. Act. Index - 28 Days % min.	85										75		75	75	75
w/lime psi min.	800													900	900
Water Requirement % max.	105													(5)	(5)
Shrinkage % max.	0.03	0.09												N.S.	N.S.
Soundness % max.	0.50													.50	.50
Expansion 14 day % max.	0.02													N.S.	N.S.
FA Proportion Specified			20% by wt.	25% by wt.	100 lb. per cy no red. in PC	94 lb. per cy		equal vol. to 1 bag	used 72 lb. FA to repl. 47 lb. PC	used 75 lb. FA per cy	10% by wt.	(8) 15%	(8) 15%		

NOTES:

(1) Special Provision
(2) Optional test
(3) Sub-bituminous and lignite coal sources
(4) cm^2/gm
(5) This specification requires that a mortar of fly ash pozzolan and 103 percent of the water content of the control shall have a flow equal to or greater than that of the reference mortar.
(6) Uniformity requirements not presented
(7) Not specified
(8) Weight or volume replacement not specified

maximum; and

d) A uniformity requirement on the fineness, as measured by the percent retained on the #325 sieve, has been added.

As this review specification has not been approved, the above are presented only for informational purposes and distribution of the Class C requirements is considered inappropriate at this time.

Other federal agencies, Federal Housing Administration, Federal Aviation Administration and U. S. Department of the Navy, have issued their own specifications, but all cite the ASTM specification as a guide.

The highway departments of most states which have significant fly ash production also have specifications for inclusion of fly ash in subgrade, subbase and base courses. Acceptance of these specifications is usually based on the performance records of the materials in those states (10).

2.2 Fly Ash-Lime Stabilization

2.2.1. General

Available references relative to the use of lime-fly ash in soil stabilization are listed in the reference section of this report. The literature has been reviewed and summarized in logical categories which are then presented in the section entitled Subject Index to References, immediately following the references. In addition, outstanding or particularly relevant comment from the literature has been summarized in this section.

The literature available on the use of fly ash is voluminous. The scope of the presentation here is necessarily limited to highly selective comment on each topic. As in the Subject Index to References, topics in this section are organized in alphabetical order for easy reference.

2.2.2. Chemical Additives and Accelerators

A number of chemicals used in trace amounts have proven effective in the laboratory by both accelerating strength gain and possibly increasing the ultimate strength of the material. Agents such as calcium chloride and sodium carbonate have increased 7-day strength as much as 60 times and 120-day strengths 2 times (23). Cement added in amounts of 1% $\pm$ can also accelerate curing by as much as three weeks (65). In field trials, sodium silicate solutions increased bearing strength, determined from plate loading tests, by as much as four times over that of the untreated lime-fly ash-soil mixes. The silicate crust formed by the addition of sodium silicates also acted as a moisture shield, keeping out excess water (45).

2.2.3. Curing Conditions

Curing conditions have a tremendous effect on the strength and durability characteristics of a lime-fly ash-soil mixture. The pozzolanic reaction between lime and fly ash is most sensitive to temperature (67). High temperature cures (120^{o}F, 49^{o}C) have greatly accelerated early strength developement. The rate of gain in tensile strength is primarily a function of temperature (42, 50, 67). Temperatures below 50^{o}F (10^{o}C) have produced no appreciable strength gain in lime-fly ash-soil mixes (50). For this reason cut off dates for the construction of fly ash pavements in cold-weather states have been established to insure that sufficient strength gain is achieved before the pavement is put into service (51). Increased long term strengths have been achieved in the laboratory when samples were completely sealed to prevent any moisture loss during curing (25, 42). Other factors aiding in the increased strength of fly ash mixes are longer curing times and a combination of moist and immersed curing (42).

2.2.4. Fatigue Due to Repeated Loading

Repeated flexural loads applied to lime-fly ash-aggregate mixtures caused the material to fracture at stresses considerably below the static strength. The stress level and number of cycles to produce failure were related; a small reduction in applied stress greatly increased the number of cycles required to cause failure (3). Increased curing prior to loading also increased the number of cycles required to cause failure (7). Because of the slow but constant strength gain of pozzolanic materials, pavements made of these materials that do not fail during the first several days of loading will probably not fail due to repeated load applications only (7).

2.2.5. Field Performance

Lime-fly ash stabilized soils have found widespread use throughout the country. Applications include highways, airfields, agricultural uses, heavy structural fills, and numerous others, (18, 32, 38, 54, 57, 72, 77, 78, 82, 128). Freeze-thaw durability and resistance to frost damage have been good in cold-weather applications (56, 72). Lime-fly ash mixes have been called the strongest subbase and base materials per dollar in the country today (128).

2.2.6. Fly Ash Quality and Characteristics

Desireable fly ash properties, in relation to soil stabilization with lime, include a low loss on ignition (LOI), high surface area (Blaine fineness), high proportion of specific gravities in the range of 2.1 to 2.7, and a high SiO_2 plus Al_2O_3 content (105). Of these properties, LOI, which is a direct measure of carbon content, is probably the most important and seems to be a reliable indicator of pozzolanic reactivity of fly ashes with lime (24). The amount retained on the number 325 sieve is a less direct measure of carbon content in fly ash, the carbon content having a high inverse correlation with strength (124). Some fly ashes exhibit cementitious properties in themselves without the addition of lime. In granular soils, these fly ashes, in the right combination, are sufficient to stabilize the soils without lime additions (68). Fly ashes of this type usually derive their cementitious properties from high CaO contents in the fly ashes themselves (105).

2.2.7. Freeze-thaw Durability

The freeze-thaw durability of a lime-fly ash-soil mixture was shown to be heavily dependent on the density of the mix as well as proportions of the constituents, gradation of the soil, and length of curing prior to the onset of testing (4, 8, 42, 55). Molding to modified rather than standard Proctor densities can greatly increase the freeze-thaw durability (55). The addition of portland cement can also be beneficial to freeze-thaw durability (25). Standard testing procedures seem to lead to conflicting and often erroneous data and do not take into account such important factors as cooling and warming rates, indicating a need for revised test procedures (29). High correlations betwen freeze-thaw durability and tensile strength have been established along with the following general guidelines: tensile strength less than 50 psi (3.5 Kg/cm^2) means poor durability, 50 to 80 psi (3.5 to 5.6 Kg/cm^2) means marginal durability and over 80 psi (5.6 Kg/cm^2) indicates good freeze-thaw durability (50, 51, 82).

2.2.8. Molding Conditions and Compaction

An increase in the molded density of a lime-fly ash-soil mixture greatly increases strength (55, 69, 75, 121). A 10% increase in the density of some mixtures can result in a doubling of compressive strength (121). As previously mentioned, molding to modified rater than standard Proctor densities can also greatly increase the freeze-thaw durability (55). Maximum soaked unconfined compressive strength is not necessarily obtained at the optimum moisture content; sandy soils attain maximum strength when compacted below optimum moisture content whereas clayey soils reach their maximum strength when compacted above optimum. Increased curing periods required increased moisture contents for maximum strength, also. Clayey soils can lose ultimate strength if the mixing temperatures are too high, suggesting pre-compaction reactions; delays in compaction after mixing of some other soils also results in strength losses (69).

2.2.9. Special Test Methods

In order to properly assess the characteristics of lime-fly ash mixes, new test procedures and new applications of existing test procedures have been utilized by researchers. Triaxial and California Bearing Ratio tests have been performed on lime-fly ash mixes and the results discussed (77). An indirect measure of strength has been made by measuring the water absorption of a mix and utilizing the strong correlation between water absorption and strength (75). Autoclave curing of lime-fly ash mixes yields the pozzolanic activity, another measure of possible strength, but in much less time than the standard test due to a high-temperature cure (46). Another characteristic, fatigue under repeated loading, utilizes flexural beams to determine the load and number of cycles required to produce fatigue failure (3). Suggestions have been made to change the existing freeze-thaw test procedures for lime-fly ash mixes in order to obtain more consistent and reliable results (29). An indirect measure of freeze-thaw durability has been developed by first measuring the tensile strength and then utilizing an established correlation between tensile strength and durability by applying the guidelines mentioned in section 2.2.7. (50, 51).

2.2.10. Strength Recovery

Lime-fly-ash mixes possess the unique property of strength recovery after a limited amount of structural damage, i.e. autogenous healing. If damage is done to the pavement in the early stages of curing, the lime-fly ash mix will continue its strength gain, often healing the old fractures, returning to normal strength (10).

2.2.11. Wet-Dry Durability

Wet-dry durability, much like freeze-thaw durability, is heavily dependent on the relative density of the lime-fly ash-soil mixture, the durability increasing with increasing density (4, 55). If the density of the specimen is high enough, wet-dry cycles actually improve strength and durability (55, 82). Gradation, i.e. sufficient fines to "float" the coarser aggregate, is important for good wet-dry durability. An excess of fines is preferable to a deficiency. Longer curing as well as increased fly ash contents also contribute to increased wet-dry durability (4).

2.3 Proportioning Techniques

Methods for proportioning of lime-fly ash-soil mixtures for highway construction are few in current literature. However, at least two methods are available at present. The first method utilizes predetermined lime and fly ash ratios which are dependent on the type of soil being stabilized. For example, by this method a granular soil would require 3 to 6% lime and 10 to 25% fly ash while a clayey soil would need 5 to 9% lime and 10 to 25% fly ash (71). A second method, used mainly for portland cement-fly ash stabilization for base courses, simply specifies that a mix must achieve a 7 day unconfined compressive strength of 400 to 450 psi (28 to 32 Kg/cm^2) and then increase with continued curing (74). Both of these methods must employ high factors of safety.

2.4 Pavement Design

Two methods for pavement design were discussed in the literature. The first method involves a detailed analytical analysis of a lime-fly ash-aggregate mixture. A series of equations is used to relate pavement thickness to flexural strength, modulus of elasticity, subgrade support value, critical load, loaded area, type of loading and safety factor (2). The second method utilizes the AASHO design method and structural coefficients specially derived for fly ash mixes (118).

CHAPTER 3. SOILS AND MATERIALS

3.1 General

Materials utilized in the study were obtained in Arizona, or from producers immediately adjacent to Arizona, and were selected on the basis of potential use in Arizona highway construction. Lime and fly ash were obtained from commercial production runs and were not specially produced for use in the study. Four distinctly different soil types were selected, each of which has been encountered in street and highway construction at various locations throughout the state. Characteristics and performance of the soils have been established, relative to highway construction, through wide experience.

3.2 Soils

3.2.1 General Descriptions

Four soils were utilized in the program, each common to a different area of the state: clayey sand, poorly graded sand, highly plastic clay, and volcanic cinders. Throughout the remainder of the report the four soil types will be identified by the simplified terms clayey sand, sand, clay and cinders, respectively. The Arizona Department of Transportation (ADOT) supplied representative samples of the soils to Engineers Testing Laboratories (ETL), obtained from the locations noted on Figure 3-1.

The clayey sand was brown, medium to well graded, with low plasticity and dry strength. The sand was tan, medium to fine and poorly graded, with no plasticity or dry strength. The clay was brown to reddish brown, with high plasticity and dry strength. The cinders were of volcanic origin, grey, poorly graded with no plasticity or dry strength.

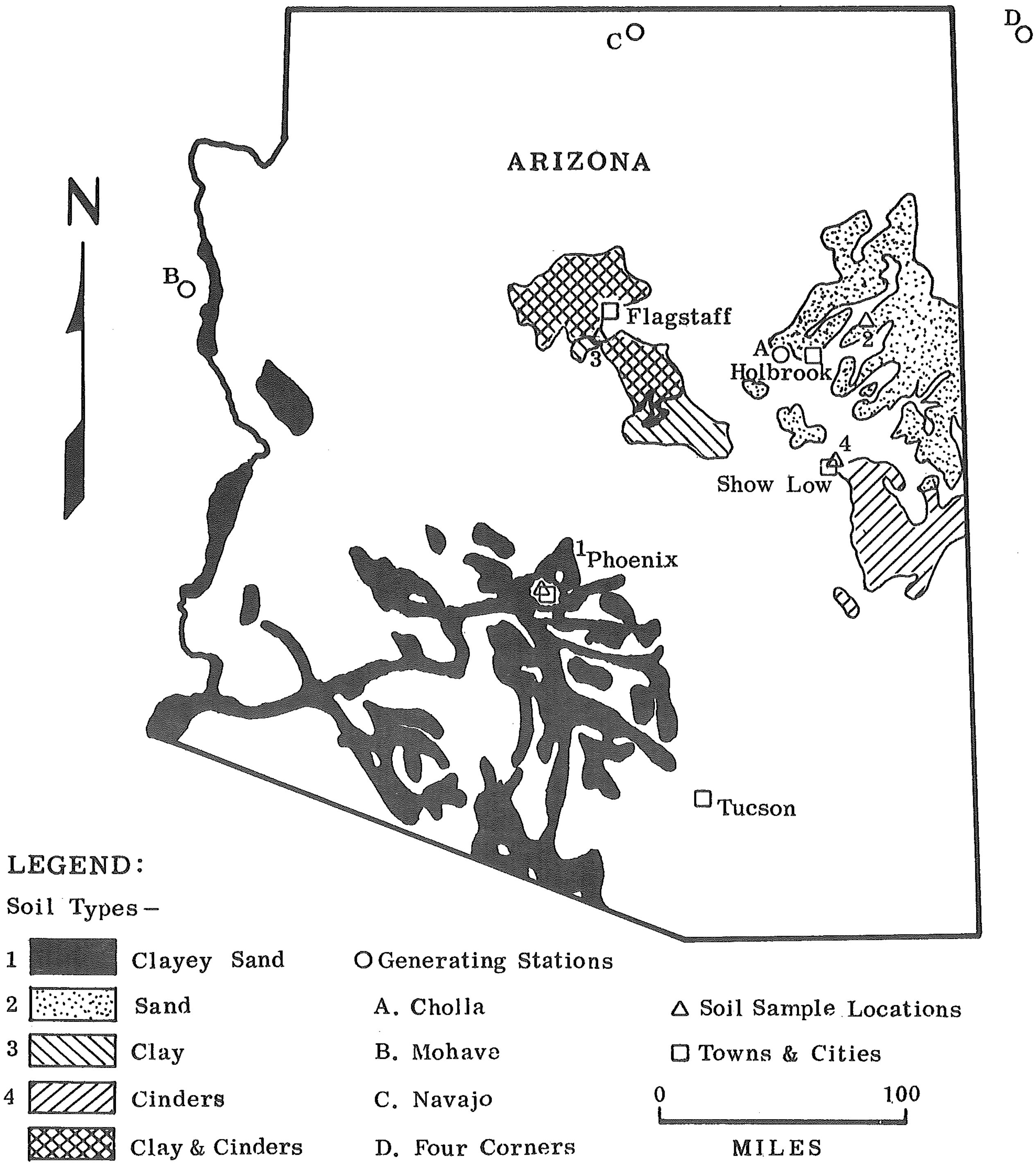


FIGURE 3-1. LOCATIONS OF FLY ASH SOURCES AND SOILS USED IN TESTING

The clayey sand was described as an hyperthermic arid soil, probably derived from erosion of surrounding mountains and weathered under climatic conditions of mean annual temperature greater than 72^{O}F and less than 10 inches mean annual precipitation. Parent rock sources consisted of a diverse suite of igneous, sedimentary and metamorphic rocks typical of the ranges surrounding the Phoenix Basin.

The sand was described as mesic semiarid soil probably derived from erosion of numerous sandstone formations and intra formational sandstone strata typical of the Plateau Province in Navajo County. Disintegration of sandstone bedrock was accelerated by large diurnal changes in temperature, intermittent rainfall and wind, under climatic conditions of mean annual temperatures ranging between 47^{O}F to 59^{O}F and 10 to 16 inches of mean annual precipitation.

Clay was described as a frigid subhumid soil probably derived from chemical weathering of basic extrusive igneous rocks under climatic conditions with mean annual soil temperatures less than 47^{O}F and more than 16 inches of mean annual precipitation.

Cinders were described as shallow talus, probably derived from mechanical disintegration of vesicular basic igneous rocks associated with volcanic vents and cinder cones.

3.2.2 Soil Properties

Grain size analyses were performed on each soil, the results of which appear in Table 3-1 and Figure 3-2. The results of further physical and chemical test series are presented in Tables 3-2 and 3-3. Test data were used to classify the soils in both the AASHO and Unified Soil Classification systems as a general basis for comparison of the four soil types.

Standard moisture-density tests were performed on the soils in accordance with AASHO Designation: T99-70. Method A was employed for the clayey sand, sand and clay, and Method C was used for the cinders. The optimum moisture contents and corresponding standard maximum densities are included in Table 3-2 and the moisture-density curves are presented in Figure 3-3.

3.3 Fly Ash

Fly ash from four available sources was utilized in this study. The sources and general locations were:

Four Corners Generating Station - near Fruitland, New Mexico

Navajo Generating Station - near Page, Arizona

Mohave Generating Station - near Laughlin, Nevada

Cholla Generating Station - near Joseph City, Arizona

Coal used at these plants was obtained from bituminous-to-subbituminous sources in Arizona and New Mexico. Information on coal sources and quality is included in Appendix A.

Test results from samples of the fly ash used in the study specimens are presented in Table 3-4. Periodic sampling and testing of fly ash from each of the sources were performed during the course of the study; however, such sampling and testing were unscheduled and incidental to this study. The data were accumulated for the purpose of providing information

TABLE 3-1. Grain Size Analysis

Grain Size		% Finer by Weight				
		Clayey Sand*	Sand *	Clay *	Clay **	Cinders **
Inches	1 1/2					100
	1					96
	3/4				100	94
	1/2				99	87
	3/8				99	75
	1/4				99	46
U. S. Standard Sieve Sizes	# 4	100	100	100	98	27
	# 8	93	98	98	96	11
	# 10	91	98	98	96	9
	# 16	84	96	97	95	6
	# 30	73	85	95	94	4
	# 40	68	69	94	93	3
	# 50	63	44	94	93	2
	#100	52	14	92	91	1
	#200	38	7	89	88	1
mm	0.050		4			<0.1
	0.042	27				
	0.037			82	81	
	0.035		3			
	0.031	21				
	0.027			73	74	
	0.022		3			
	0.020	16				
	0.018			64	64	
	0.013		3			
	0.012	14				
	0.011			56	56	
	0.009	12	3			
	0.008			52	52	
	0.007		3			
	0.006	11	3	48	48	
	0.003	9	2	42	42	
	0.001	8	2	37	37	

*Minus #4 Material Only

**As Received

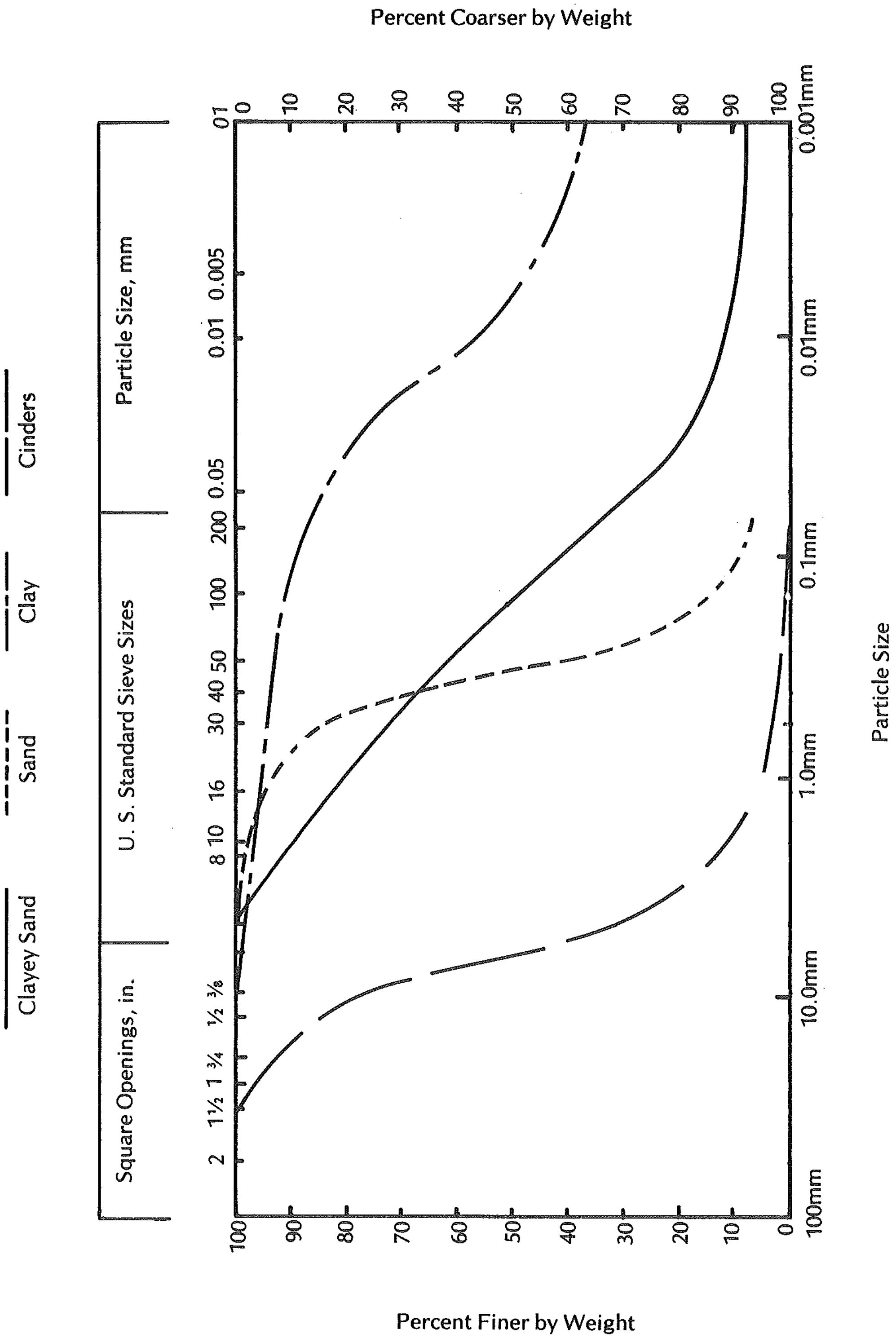


FIGURE 3-2. PARTICLE SIZE DISTRIBUTION CURVES.

TABLE 3-2. Engineering/Index Properties

PROPERTY	SOIL			
	Clayey Sand	Sand	Clay	Cinders
Unified Soil Classification	SC	SP	CH	GP
AASHO Classification	A-4	A-3	A-7-6	A-1-a
Specific Gravity of Solids	2.70	2.66	2.76	2.59 (2)
Atterberg Limits Liquid Limit Plastic Limit Plasticity Index	 22 18 4	 14 NP(4) NP	 63 17 46	 NP NP NP
Resistance Value	69	75	<5	-
Bulk Density (3) SSD OD Absorption, %	-	-	-	 1.68 1.37 23.1
Maximum Dry (1) Density, pcf	128	112	103	61
Optimum (1) Moisture Content, %	10	13	21	29

NOTES:

1. AASHO: T99-70
2. Minus #4 Material Only
3. Plus #4 Material Only
4. Non-Plastic

TABLE 3-3. Chemical Characteristics of Soils Used. *

Soil	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Cation Exchange Capacity
Clayey Sand	28.19	3.15	0.64	0.72	32.70
Sand	14.47	0.26	0.07	0.54	15.34
Clay	47.41	14.06	0.42	0.68	62.57
Cinders	17.47	3.10	0.46	0.81	21.84

*Results are expressed as milliequivalents per 100 grams air dry soil.

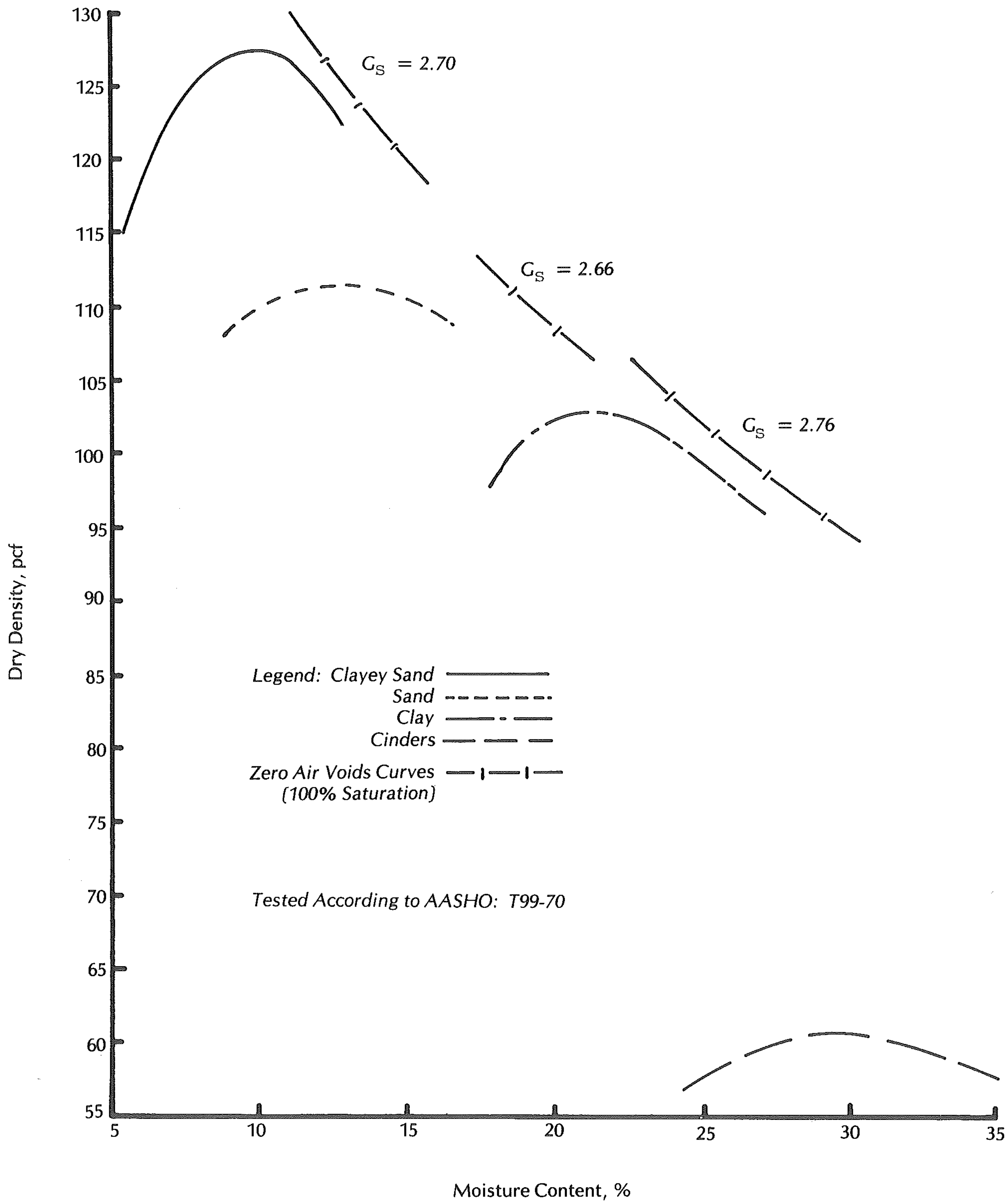


FIGURE 3-3. SOILS COMPACTION CURVES.

TABLE 3-4. Fly Ash Used in Strength and Durability Test Specimens

Property	Cholla *	Four * Corners	Navajo **	Mohave **	ASTM: C 618 Class F Specifications
SiO_2 %	58.4	58.4	52.7	52.6	
Al_2O_3 %	31.4	31.4	20.5	16.3	
Fe_2O_3 %	1.3	0.8	4.9	5.5	
Sum of oxides %	91.1	90.6	78.1	74.4	70.0 min.
MgO %			2.0	2.5	-
SO_3 %	0.3	0.3	0.5	1.13	5.0 max.
Moisture %	0.01	0.04	0.02	0.02	3.0 max.
Loss on Ignition %	0.34	0.44	2.77	0.77	12.0 max.
Available Alkalies					
As Na_2O %	0.28	0.52	1.31	1.14	1.5 max.
CaO %	4.5	3.3	8.7	16.4	-
Fineness					
Surface Area cm^2/cm^3	4560	5000	6835	9145	6500 min.
Retained #325 %	36.2	29.8	34.4	36.2	34 max.
Multiple Factor %	12.3	13.1	95.3	27.9	255.0 max.
Pozzolanic Activity Index:					
Cement, % control	60.0	56.0	67.0	84.0	85 min.
Lime, psi	-	-	-	-	800 min.
Water requirement					
% of control	102	98.5	-	-	105 max.
Shrinkage,					
Increase %	0.077	-	-	-	0.03 max.
Soundness,					
Autoclave %	0.048	0.048	0.053	0.13	0.5 max.
Expansion - 14 day %	-	-	-	-	0.02 max.
Air-Entraining Admixture ml.	1.68	1.44	-	-	Not applicable
Specific gravity	2.07	1.92	2.12	2.46	Not applicable
Cation Exchange Capacity ***	26.6	30.5	59.4	33.9	Not applicable

*Samples obtained from commercial carriers.
**Samples obtained from storage bins.
***Expressed as milliequivalents per 100 grams air dry soil.

on the variation of fly ash properties. Test data relating to the periodic sampling as well as a discussion of the methods of fly ash recovery at each plant are included in Appendix A.

The data of Table 3-4 apply to samples which represent only the fly ash used in the strength and durability test specimens. Data in Appendix A apply to all samples, including those used in the test series.

The test results indicate that each fly ash failed in some respect to meet the ASTM Designation: C618 for Class F Pozzolan. The failures occurred in the areas of fineness (Blaine surface area and % passing the #325 sieve) and pozzolanic activity index.

3.4 Lime

High-calcium hydrated lime used in the study was produced at the City of Industry, California, plant of the U. S. Lime Division of the Flintkote Company in a regular production run. Nominal chemical test data were supplied by the manufacturer and are reported in Table 3-5.

Several choices are normally available when selecting lime for soil stabilization, including waste lime, quicklime and hydrated lime. Waste lime is frequently composed of both hydrated and quicklime, as well as impurities, and is difficult to use due to usual lack of control over quality and uniformity. Quicklime (calcium and/or calcium-magnesium oxide) has been successfully used although hazards inherent in handling have been a major objection. Hydrated lime (calcium and/or calcium-magnesium hydroxide) has apparently been most frequently used. Both high calcium and magnesium (dolomitic) limes have been successfully used. The high calcium-hydrated lime used for this study series was selected on the basis of availability as well as characteristics.

TABLE 3-5. Hydrated Lime Test Data

Property		Representative Analysis *
Acid Insoluble	%	1.5
Fe_2O_3	%	0.1
Al_2O_3	%	0.5
MgO	%	1.0
$Ca(OH)_2$	%	94.6
Pass 200 Sieve	%	97.0
Pass 325 Sieve	%	88.0

*Flintkote California High Calcium Hydrated Lime. Test data are typical analyses provided by the manufacturer.

3.5 Lime-Fly Ash-Soil Combinations

At least three distinct phenomena have normally been associated with the addition of lime and fly ash. The first reaction tends to lower the plasticity and give the soil a more friable appearance immediately upon mixing. This change in itself frequently results in a significant improvement in the engineering characteristics of the soil. The second phenomenon involves the apparent reaction between the calcium and available silica or alumina (in soil or fly ash) which results in the formation of a matrix of one or more cementitious compounds. This reaction is relatively slow at normal temperatures, usually requires several days to be measurable to any significant degree and continues over a period of months and possibly years (pozzolanic reaction). The third and slowest reaction involves absorption of carbon dioxide from the air and the formation of calcium carbonate. This last reaction is not considered significant in the context of soil stabilization. The results of the pozzolanic reaction were the primary subject of this study.

The lime-fly ash-soil combinations selected for strength and durability testing were subjected to a preliminary test series to establish moisture-density relationships and relative plasticity.

The moisture-density testing was performed in accordance with AASHO Designation: T99-70, Method A for all Cholla fly ash combinations without cinders and Method C for all combinations with cinders. The standard maximum dry densities and corresponding optimum moisture contents are presented in Table 3-6 for all Cholla fly ash tested.

To evaluate plasticity, Atterberg limits tests were performed on the lime-fly ash-soil combinations in accordance with AASHO Designation: T89-68 and T90-70, the results of which are presented in Table 3-7. The clay was the only soil with appreciable plasticity, and some conclusions can be drawn from the

TABLE 3-6. Compaction Data for Lime-Fly Ash-Soil Combinations

Soil	% Lime	% Fly Ash** 0	10	20	30
Clayey Sand	0	128 @ 10*	122 @ 11	117 @ 11	113 @ 12
	2	128 @ 11	116 @ 12	112 @ 12	107 @ 13
	4	124 @ 11	116 @ 11	112 @ 11	109 @ 11
	6	120 @ 12	114 @ 12	112 @ 12	110 @ 12
	8	116 @ 12	111 @ 14	110 @ 14	107 @ 14
Sand	0	112 @ 13	114 @ 10	116 @ 9	115 @ 10
	2	113 @ 12	116 @ 9	115 @ 9	111 @ 10
	4	115 @ 12	116 @ 9	115 @ 9	112 @ 10
	6	116 @ 12	116 @ 9	115 @ 9	114 @ 10
	8	118 @ 11	***	***	***
Clay	0	103 @ 21	102 @ 19	100 @ 20	99 @ 20
	2	102 @ 21	102 @ 19	99 @ 19	95 @ 17
	4	101 @ 21	98 @ 20	97 @ 18	95 @ 16
	6	96 @ 22	97 @ 21	95 @ 18	96 @ 19
	8	95 @ 22	***	***	***
Cinders	0	61 @ 29	***	78 @ 29	***
	2	***	***	79 @ 29	***
	4	63 @ 36	74 @ 32	79 @ 29	***
	6	64 @ 35	75 @ 31	79 @ 29	***

* Maximum dry density of 128 pcf at optimum moisture content of 10% according to AASHO: T99-70, Method A for all except Cinders combinations, Method C for Cinders combinations.

** Cholla Fly Ash

*** Combination not tested.

TABLE 3-7. Atterberg Limits of Lime - Fly Ash - Soil Combinations.

Soil	% Lime	% Fly Ash											
		0			10			20			30		
		LL	PL	PI	LL	PL	PI	LL	PL	PI	LL	PL	PI
Clayey Sand	0	22	18	4	NP	NP	NP	NP	NP	NP	NP	NP	NP
	2	26	21	5	NP	NP	NP	NP	NP	NP	NP	NP	NP
	4	30	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
	6	33	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
	8	32	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Sand	0-8	All Combinations Non-Plastic											
Clay	0	63	17	46	56	15	41	53	17	36	50	18	32
	2	45	34	11	41	28	13	40	28	12	40	30	10
	4	44	34	10	47	33	14	43	32	11	38	28	10
	6	50	36	14	47	33	14	44	30	14	40	30	10
	8	49	36	13	48	33	15	40	29	11	38	27	11
Cinders	0-6	All Combinations Non-Plastic											

lime-fly ash-clay combination data presented in Figure 3-4.

Generally, the addition of fly ash decreased the liquid limit, plastic limit, and plasticity index of the mixture, regardless of the lime content. The test results also indicated that the addition of 2% lime to any combination of fly ash and clay, or clay alone, reduced the liquid limit and increased the plastic limit, and thereby significantly reduced the plasticity index of the combination.

These preliminary test data are presented as a part of this materials section to aid in the description and classification of the soils considered in the study.

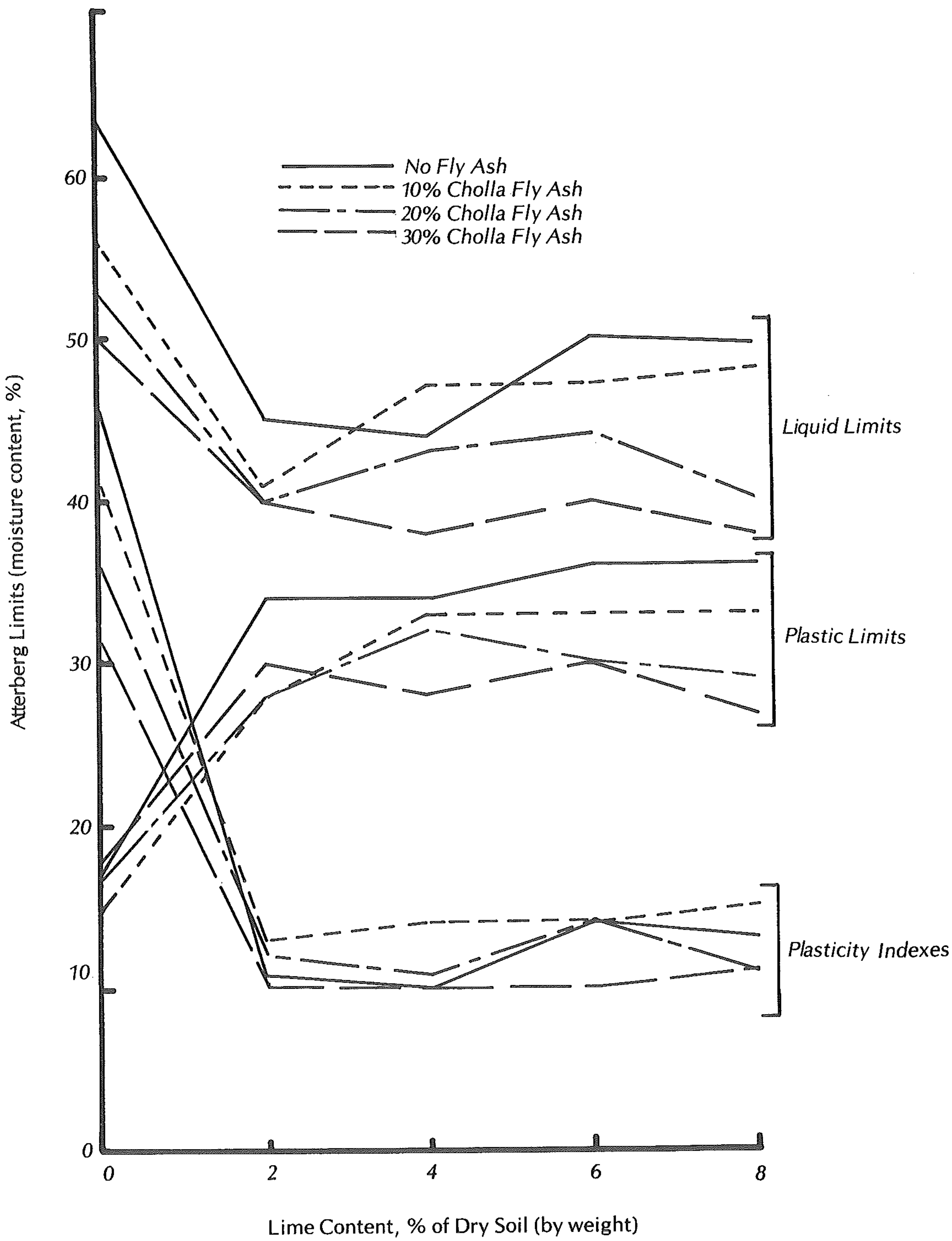


FIGURE 3-4. ATTERBERG LIMITS OF LIME-FLY ASH-CLAY COMBINATIONS.

CHAPTER 4. STRENGTH CHARACTERISTICS

4.1 General

The effects of various combinations of lime and fly ash on unconfined compressive strength were evaluated for each of the four soil types. The major test series, discussed in this chapter, was conducted on specimens which were tested at molding water content. This procedure had the effect of avoiding one uncontrolled variable, degree of saturation, which would be expected to influence compressive strength. The data therefore provided a basic assessment of the effects of lime and fly ash proportions on the unconfined compressive strength of each soil type. The effects of saturation on unconfined compressive strength are discussed in a later section on durability.

A broad range of lime-fly ash-soil mix combinations was tested for each soil type. Lime proportions were varied from 0 to 8% (by weight of dry soil) in increments of 2%. Fly ash proportions were varied from 0 to 30% in increments of 10%. The variable considered in the laboratory test program can be most easily described by reference to the following breakdown:

Soil Type	- SC, CH, SP and GP (Unified Soil Classification designations).
Fly Ash Type	- C, M, N, F (Cholla, Mohave, Navajo and Four Corners, respectively).
Lime Content	- 0, 2, 4, 6, and 8%.
Fly Ash Content	- 0, 10, 20 and 30%.
Age at Test	- 7, 28 and 56 days.
Specimen No.	- A, B or C (three specimens averaged for each strength determination).

A specimen designated SC-4-C10-28A, for example, would identify the SC soil type with 4% lime, 10% Cholla fly ash, and one of three companion specimens to be tested at 28 days age.

4.2 Laboratory Test Procedures

Standard maximum densities were determined for each of the lime-fly ash-soil combinations, in accordance with AASHO Designation: T99-70, Method A. (ASTM Designation: D698-70, Method A), for all soil types except cinders (GP). Method C was used for cinder (GP) specimens since the Method-A would have resulted in rejecting well over half the material. Moisture density curves were developed with a minimum of five test points for each curve.

Test specimens were molded in a Harvard miniature apparatus, yielding specimens 1.3 in. in diameter and 2.8 in. high (3.3 x 7.1 cm), for the CH, SP and SC soil types. Cinder (GP) specimens were molded in 4 in. diameter by 4.6 in. high (10.2 x 11.7 cm) cylindrical molds. The relatively small Harvard miniature mold was selected for the fine grained soils primarily due to the large number of specimens needed (more than 500 for the complete series for each soil type). The coarse-grained cinder (GP) soil could not be compacted in the small molds due to large grain size. In all cases, mixtures were blended at optimum moisture content and compacted to a density at or near the standard maximum. Specimen molding data are presented in Appendix B, including the standard maximum densities and optimum moisture contents, and the as-molded densities and moisture contents.

Dry soil, lime and fly ash were machine-blended for one minute before adding water. After adding water the mixtures were machine blended for two minutes, allowed to rest for one minute, and machine-blended again for two minutes.

Specimens were molded immediately upon completion of the blending and mixing. Specimens were extruded from the molds immediately after compaction, individually sealed in 2 mil (0.05 mm) polyethylene and stored in a moist-room at a temperature of 73 $\pm$ 3^{o}F (23 $\pm$ 1.7^{o}C) and relative humidity of 90% or higher.

Unconfined compressive strength was determined using a Soil-Test triaxial shear apparatus with a proving ring for load determination and a controlled rate of strain of 1% per minute. Maximum load was recorded as the load at failure or at 20% strain, whichever occurred first. Stresses were calculated assuming a constant volume for the specimen and correcting for the strain-induced increase in cross sectional area.

4.3 Unconfined Compressive Strength

4.3.1 General

Unconfined compressive strengths were determined in the laboratory for a broad range of lime-fly ash-soil mix combinations. In each case the reported value was an average representing three companion test specimens. These data are tabulated in Appendix B.

4.3.2 Strength vs. Lime Content

4.3.2.1 Clayey Sand

The relationship between lime content and strength for various fly ash contents is illustrated by the curves of Figures 4-1A, B, C and D. Each Figure represents the complete range of data developed from the test series for a particular fly ash source.

In the no-fly-ash series, strength remained essentially constant for lime contents of 2% and above.

The Cholla fly ash did not appear to provide any increase in soil strength when not accompanied by lime. Fly ash in the amount of 10% did cause a significant increase in strength compared to the lime-only mixtures. The data indicated that strength gain was dependent on specific proportions of both lime and fly ash. With 10% fly ash, for example, no significant strength increase was noted as lime content was increased above 4%. Similar plateaus were observed with other combinations of lime, fly ash and soil.

The specimens containing Four Corners fly ash exhibited strength characteristics nearly identical to the Cholla specimens.

Mohave fly ash appeared to cause a significant increase in strength when used alone as a soil additive. Strength peaked with about 20% fly ash, yielding a value of over 400 psi (28 Kg/cm^2). Continued strength gain was noted for all increases in either fly ash, or lime content.

Navajo fly ash did not provide a strength gain when used without lime. The 30% fly ash series appeared to lose strength, compared to the 10% and 20% series except for high (8%) lime content.

The clayey sand (SC) soil exhibited relatively high increases in compressive strength with each of the fly ash types. Peak strengths for the range of proportions tested were:

Cholla	880 psi	(62 Kg/cm^2)	SC-8-C30-56
Four Corners	1110 psi	(78 Kg/cm^2)	SC-8-F30-56
Mohave	1270 psi	(89 Kg/cm^2)	SC-8-M30-56
Navajo	1130 psi	(80 Kg/cm^2)	SC-8-N30-56
No Additive	30 psi	(2 Kg/cm^2)	SC-0- 0-56

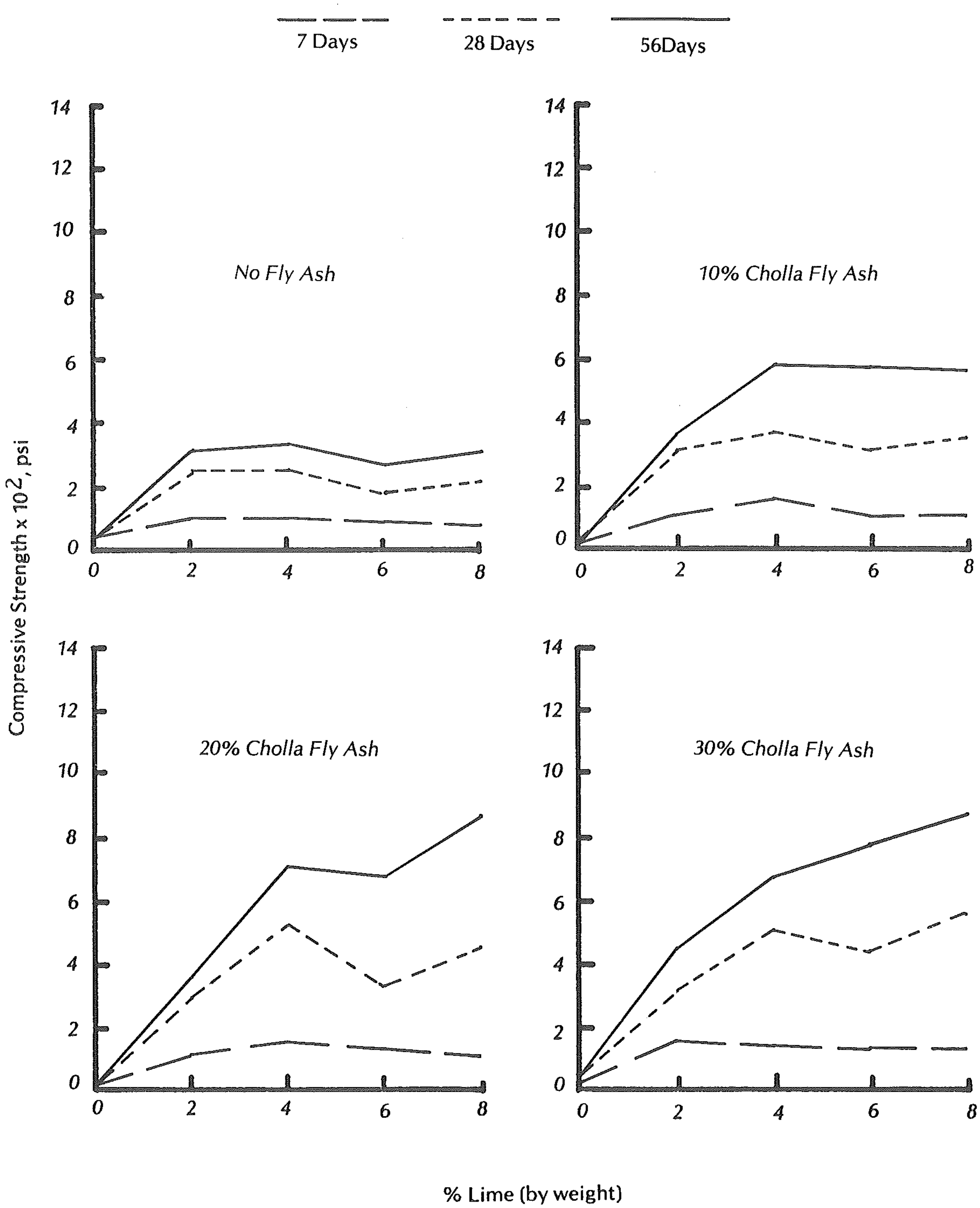


FIGURE 4-1A. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND CHOLLA FLY ASH.

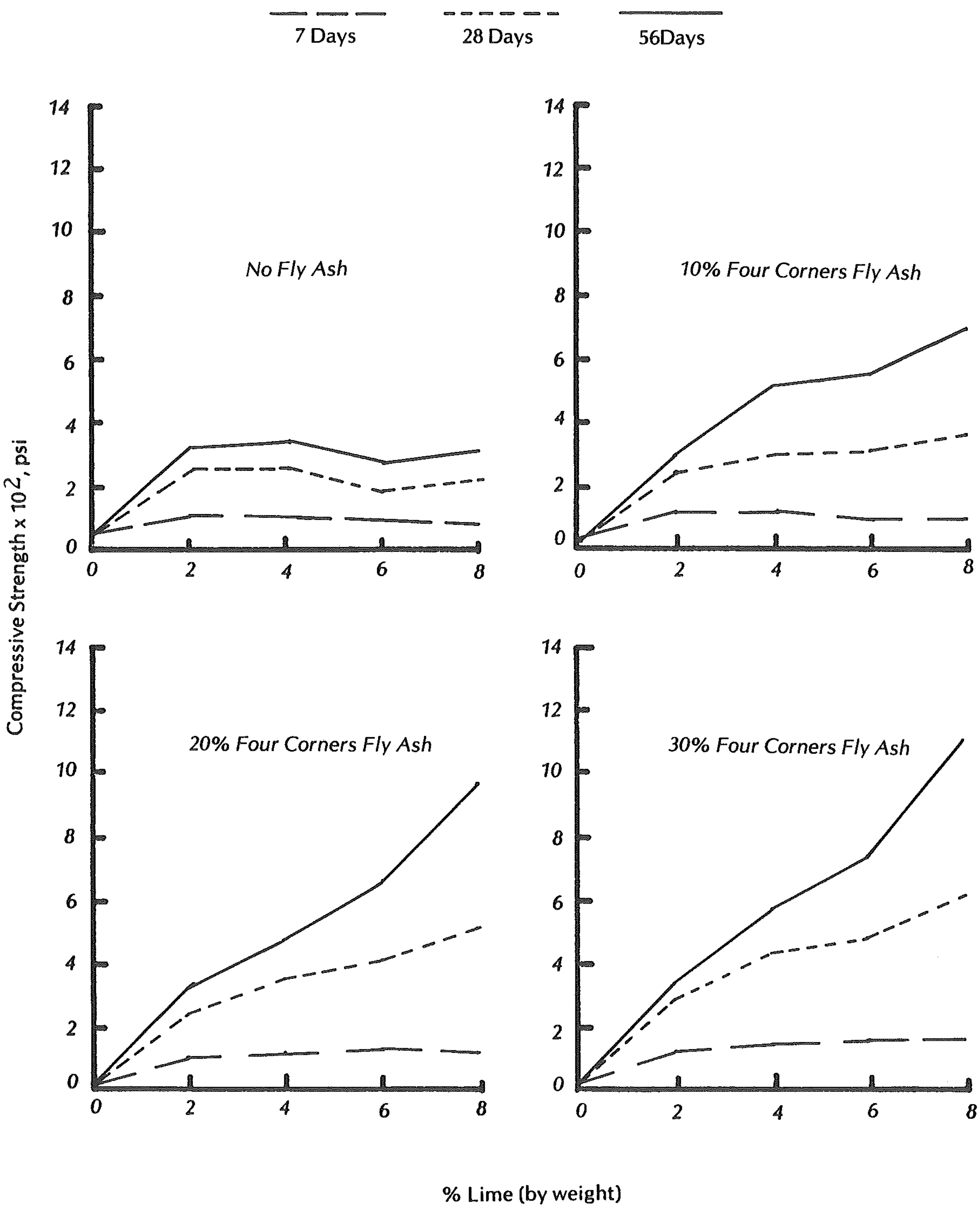


FIGURE 4-1B. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND FOUR CORNERS FLY ASH.

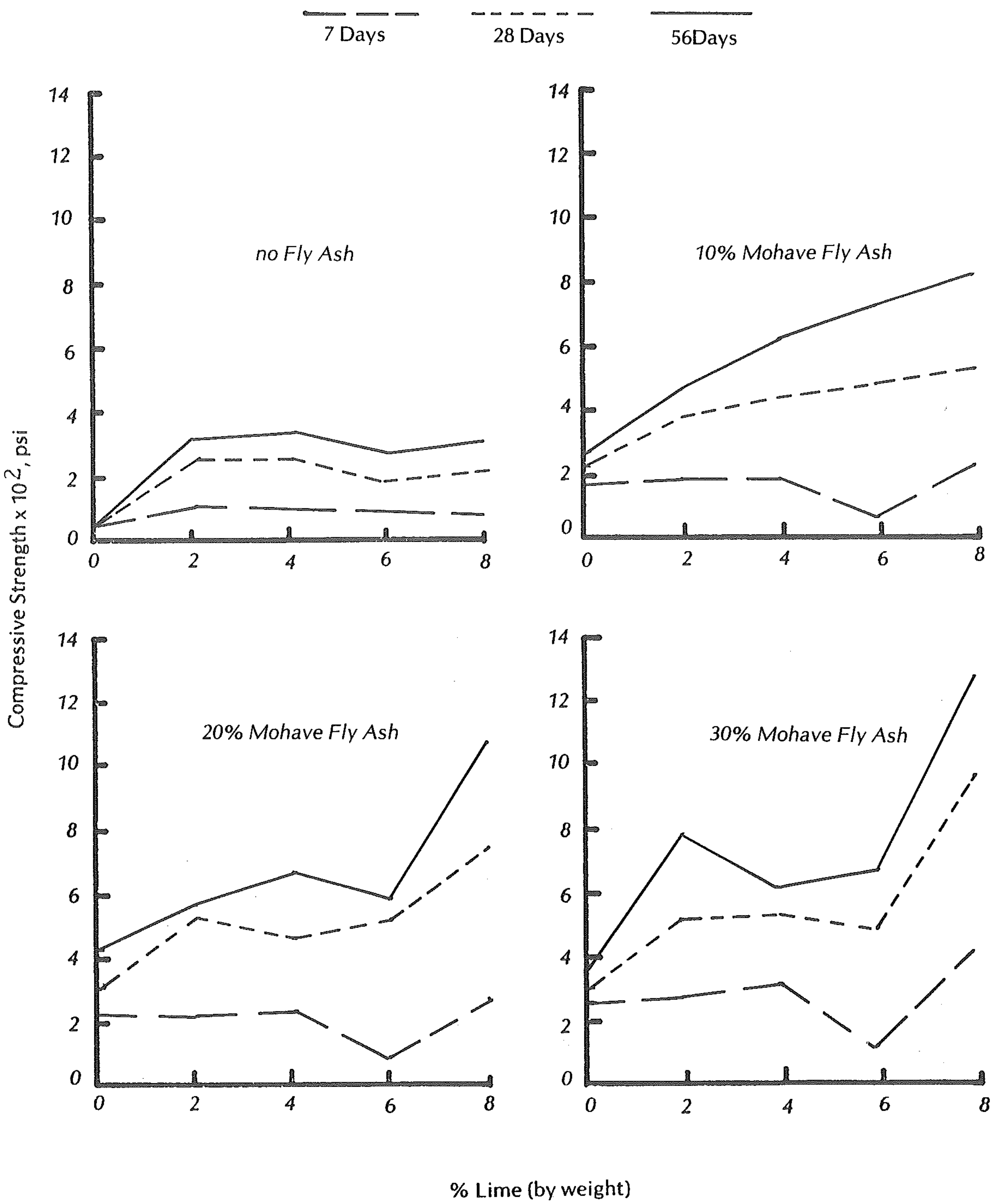


FIGURE 4-1C. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND MOHAVE FLY ASH.

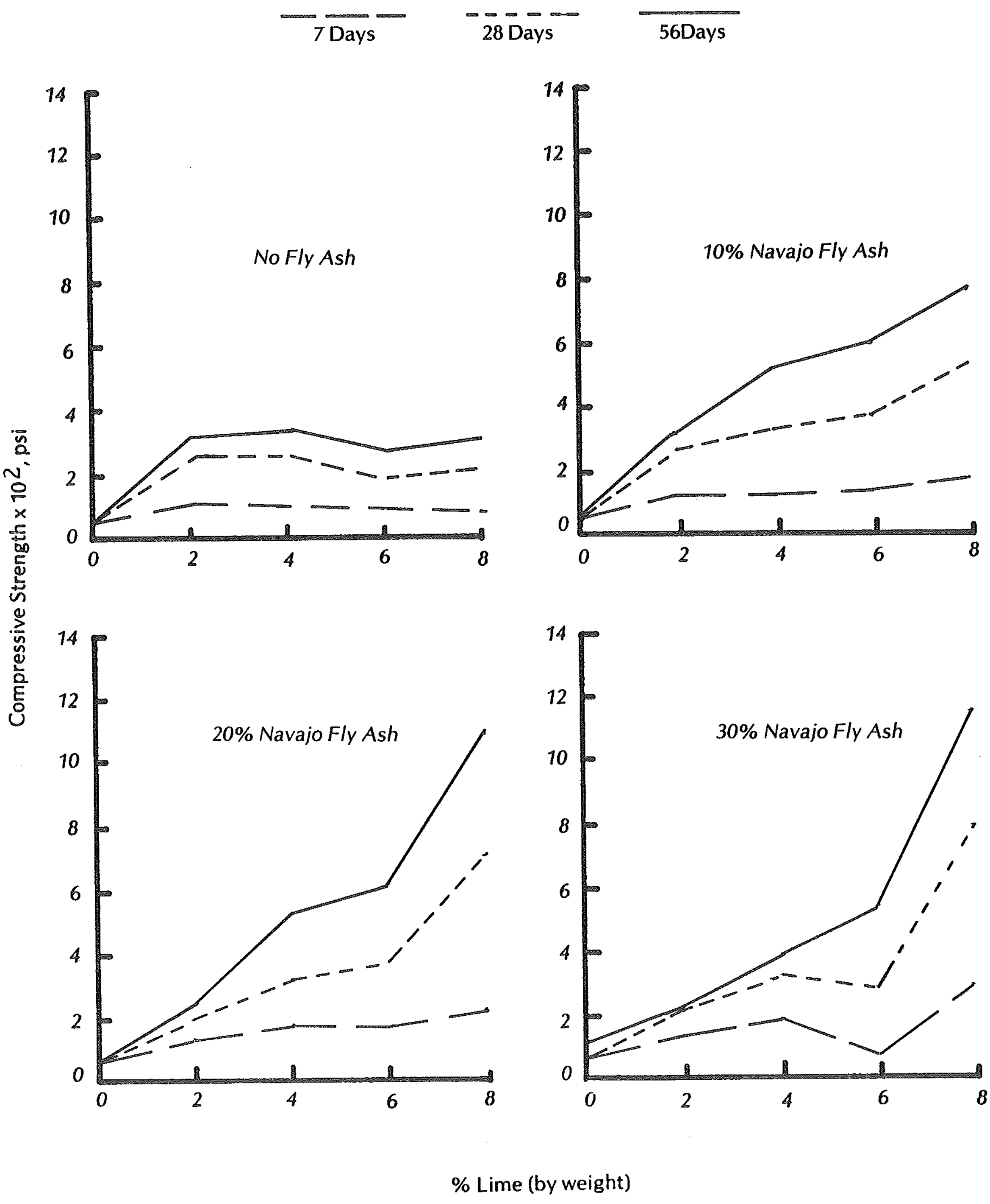


FIGURE 4-1D. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND NAVAJO FLY ASH.

4.3.2.2 Sand

The lime content-strength relationships are illustrated in Figures 4-2A, B, C and D for the sand (SP).

Test data indicated that lime, alone, was not effective in developing significant compressive strength for the sand soil type. In proportions up to 8% the addition of lime increased the strength to only about 40 psi (3 Kg/cm^2).

The Cholla fly ash increased strength significantly throughout the range of mix proportions when used in combination with lime. Used alone, in proportions of 20% or more, the fly ash resulted in minor strength gains in about the same range as for lime alone. The data tended to indicate that for a given fly ash content an optimum lime content existed above which the further addition of lime was ineffective.

Specimens molded with the Four Corners fly ash alone exhibited virtually no strength gain for any proportion of fly ash. In combination with lime the Four Corners specimens showed significant strength gain for each increase in lime or fly ash proportions.

Mohave fly ash produced some gains in strength when used alone, particularly in the 30% fly ash series. When added in combination with lime strength gains were noted for each increase in lime or fly ash content.

The Navajo fly ash resulted in noticeably less

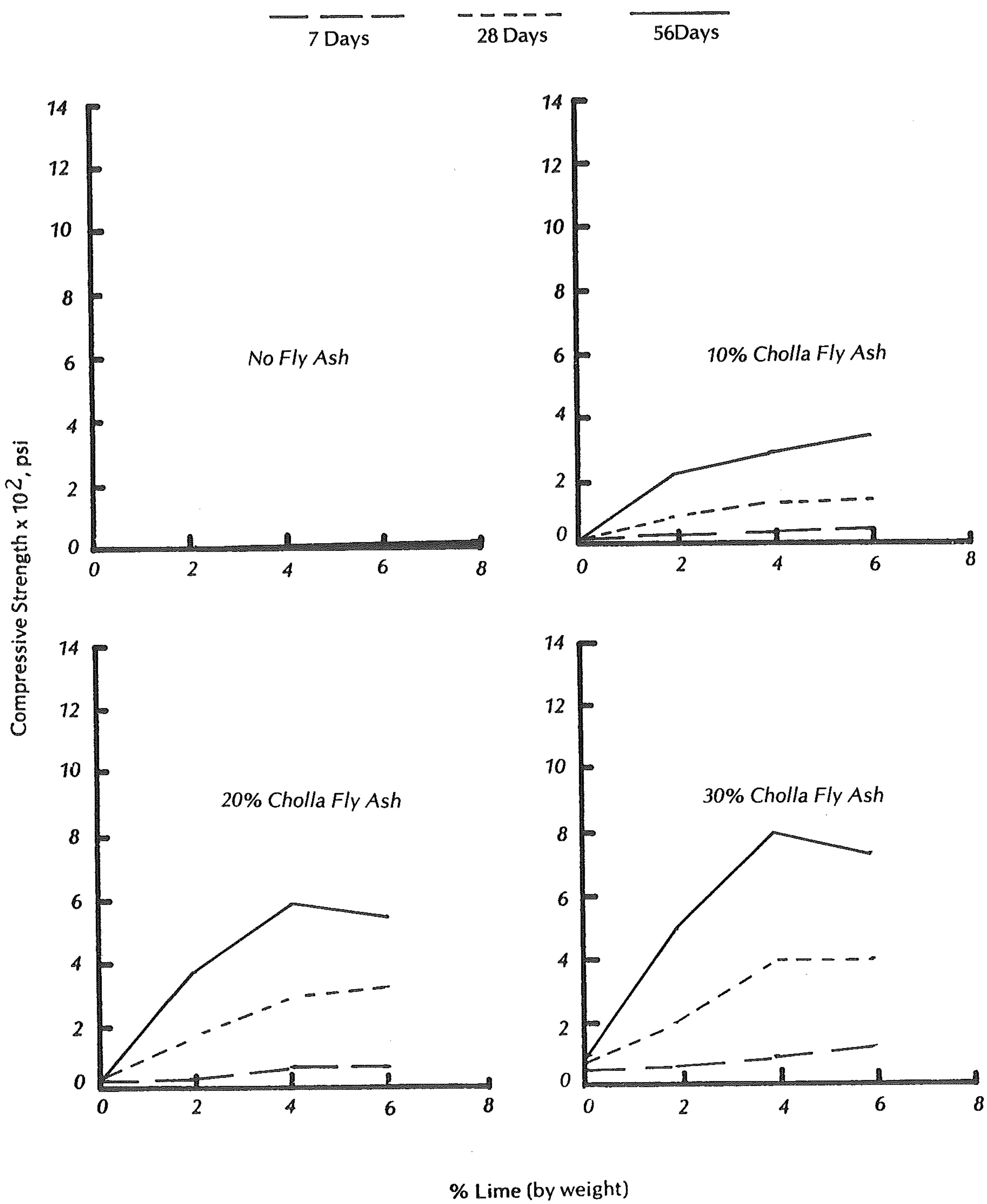


FIGURE 4-2A. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND CHOLLA FLY ASH.

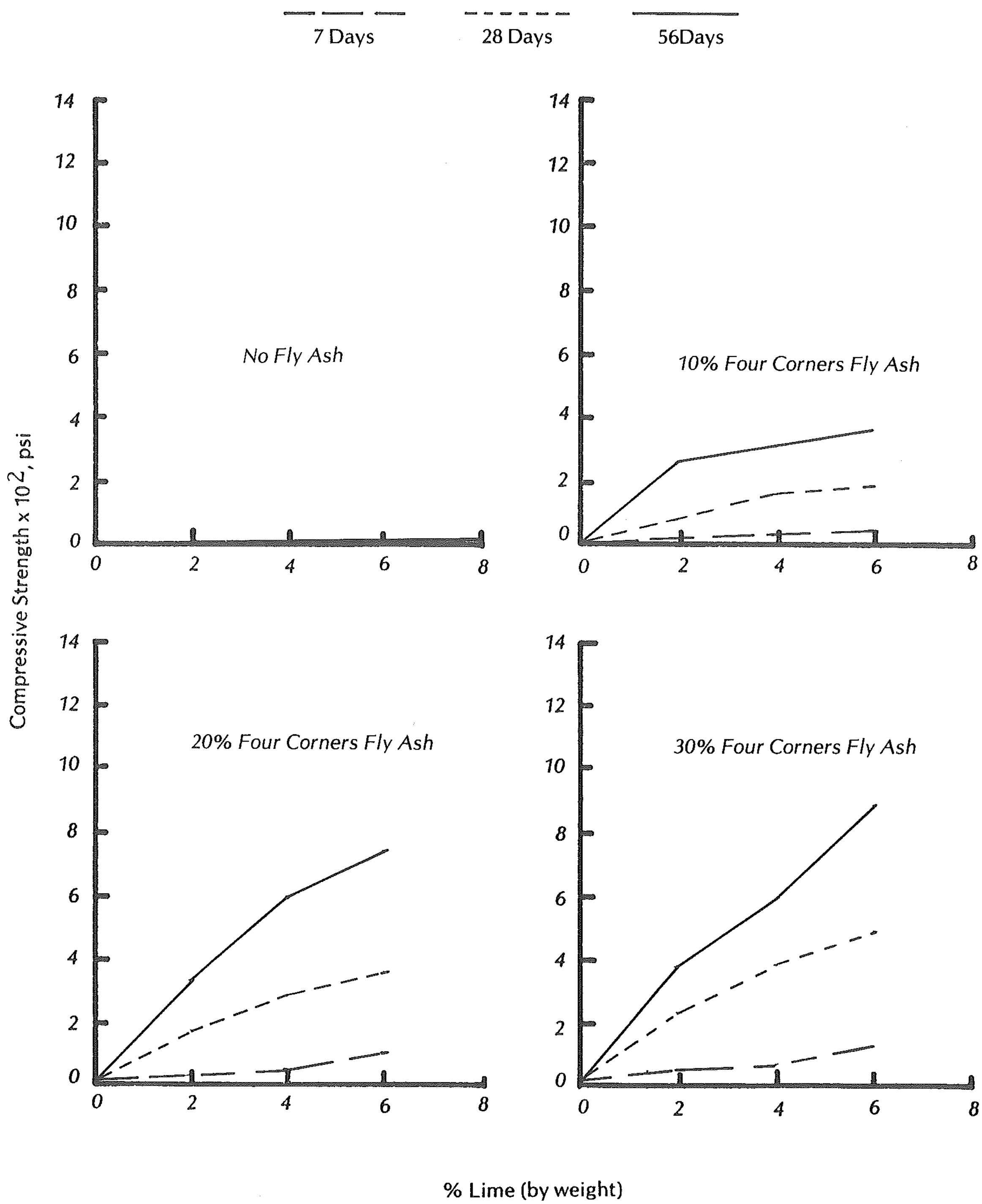


FIGURE 4-2B. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND FOUR CORNERS FLY ASH.

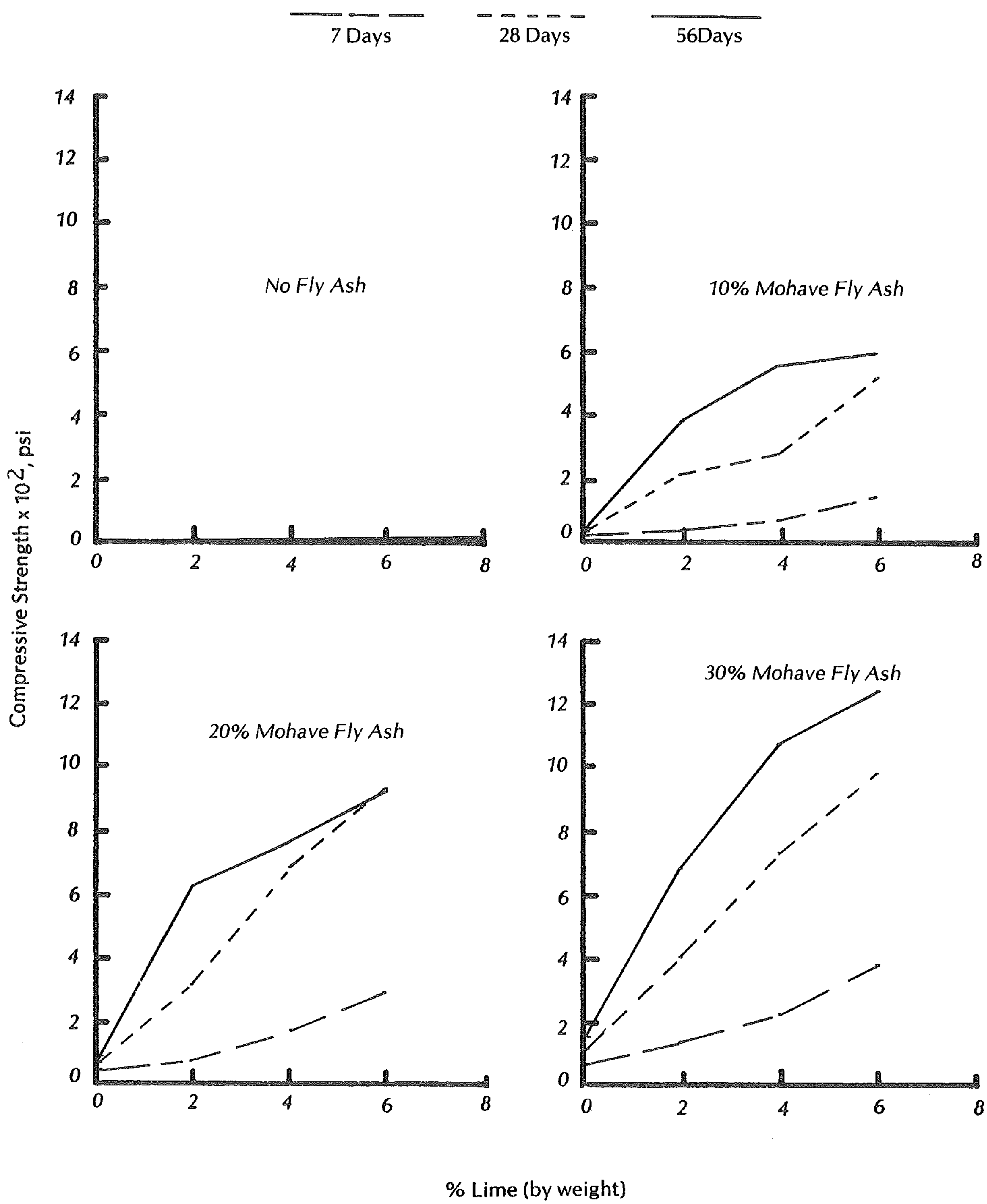


FIGURE 4-2C. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND MOHAVE FLY ASH.

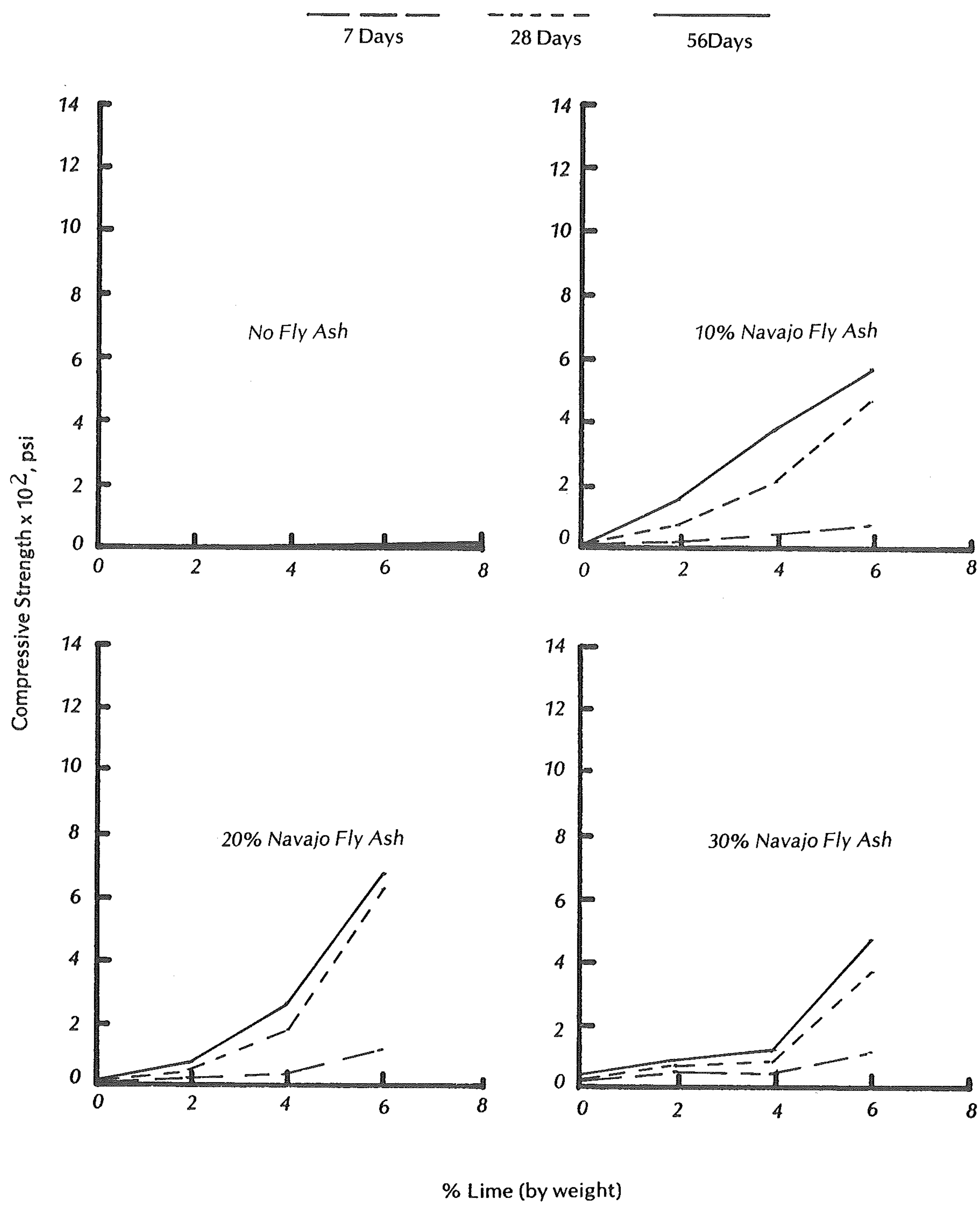


FIGURE 4-2D. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND NAVAJO FLY ASH.

significant strength gains than the other three ashes. Strength was low when lime was excluded from the mixture. Increased lime content resulted in increased strength throughout the full range of lime contents. Increased fly ash content beyond 10%, however, did not result in increased strength.

The sand (SP) soil type exhibited significant but unique compressive strength characteristics for each of the fly ash types. Peak strengths for the range of proportions tested were:

Cholla	780 psi	(55 Kg/cm^2)	SP-4-C30-56
Four Corners	870 psi	(61 Kg/cm^2)	SP-6-F30-56
Mohave	1250 psi	(88 Kg/cm^2)	SP-6-M30-56
Navajo	670 psi	(47 Kg/cm^2)	SP-6-N20-56
No Additive	0 psi		SP-0- 0 -(56)

4.3.2.3 Clay

Strength vs. lime content relationships are illustrated in Figures 4-3A, B, C and D for the clay (CH) soil type.

Test data indicated that the addition of lime alone resulted in significant strength gain. Increased lime content resulted in increased strength throughout the full range of lime contents tested.

The addition of Cholla fly ash alone (with no lime) increased strength slightly when compared to soil specimens with no additives. The

Cholla ash resulted in significant strength gains when combined with lime contents of 4% or more.

The Four Corners fly ash specimens exhibited little or no strength gain with no lime but otherwise were nearly identical to the Cholla specimens in behavior.

The addition of Mohave fly ash alone resulted in significant strength gain, particularly at the highest fly ash content (30%). Test data indicated that at the higher fly ash contents (20% - 30%), increased lime, within the range tested, was not effective in increasing compressive strength.

Navajo fly ash, without lime, resulted in a significant strength increase, about the equivalent of 2% lime and no ash. The addition of fly ash (without lime) above 10%, however, resulted in no further gain in strength. Considered overall, the Navajo ash contributed to compressive strength primarily in the specimens with no lime and 10% ash, and with 6% lime and 30% fly ash. Intermediate combinations resulted in little improvement over the use of lime alone.

The clay (CH) soil type yielded moderate unconfined compressive strength with seleceted combinations of lime and fly ash proportions. The peak strengths within the range of proportions tested were:

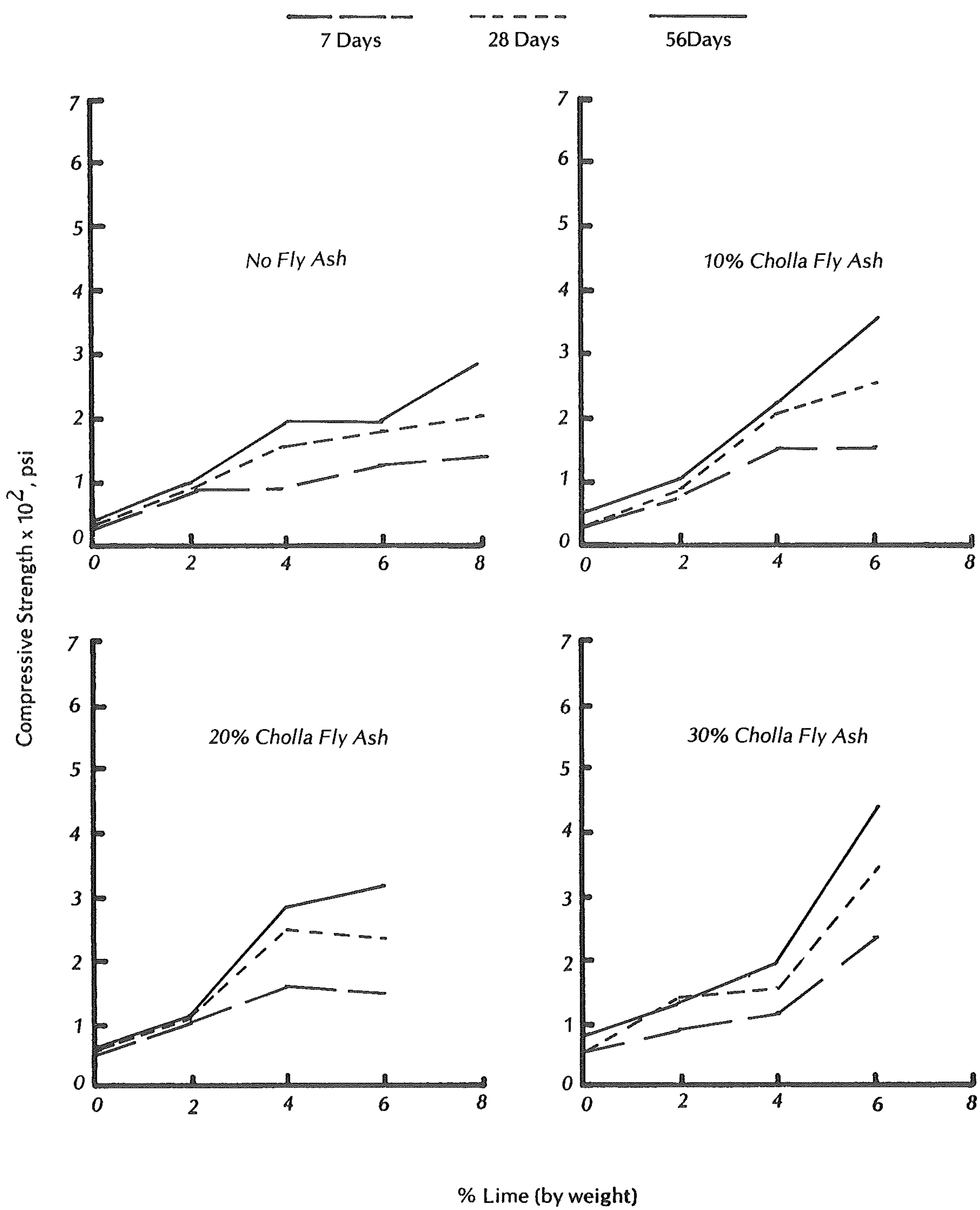


FIGURE 4-3A. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND CHOLLA FLY ASH.

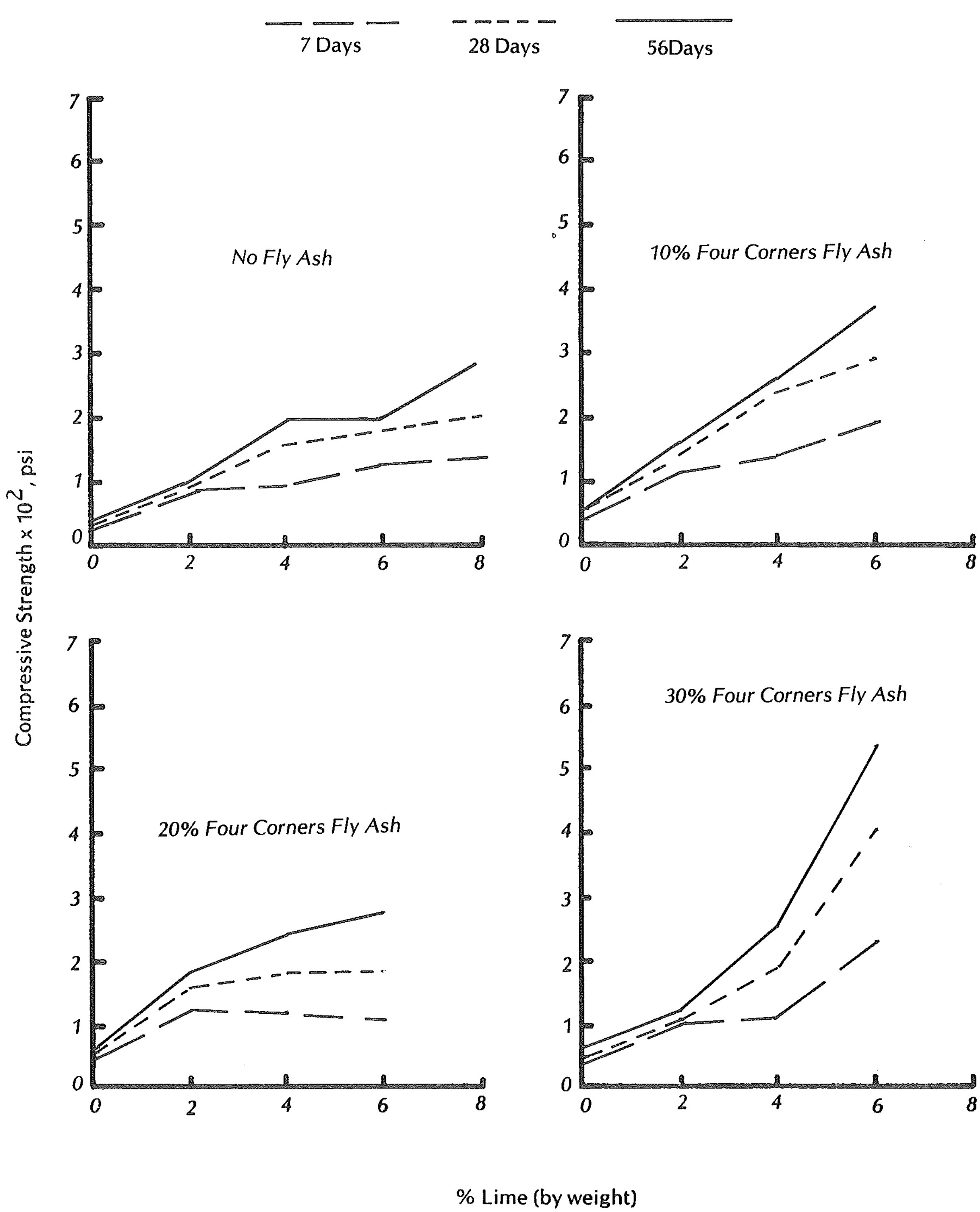


FIGURE 4-3B. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND FOUR CORNERS FLY ASH.

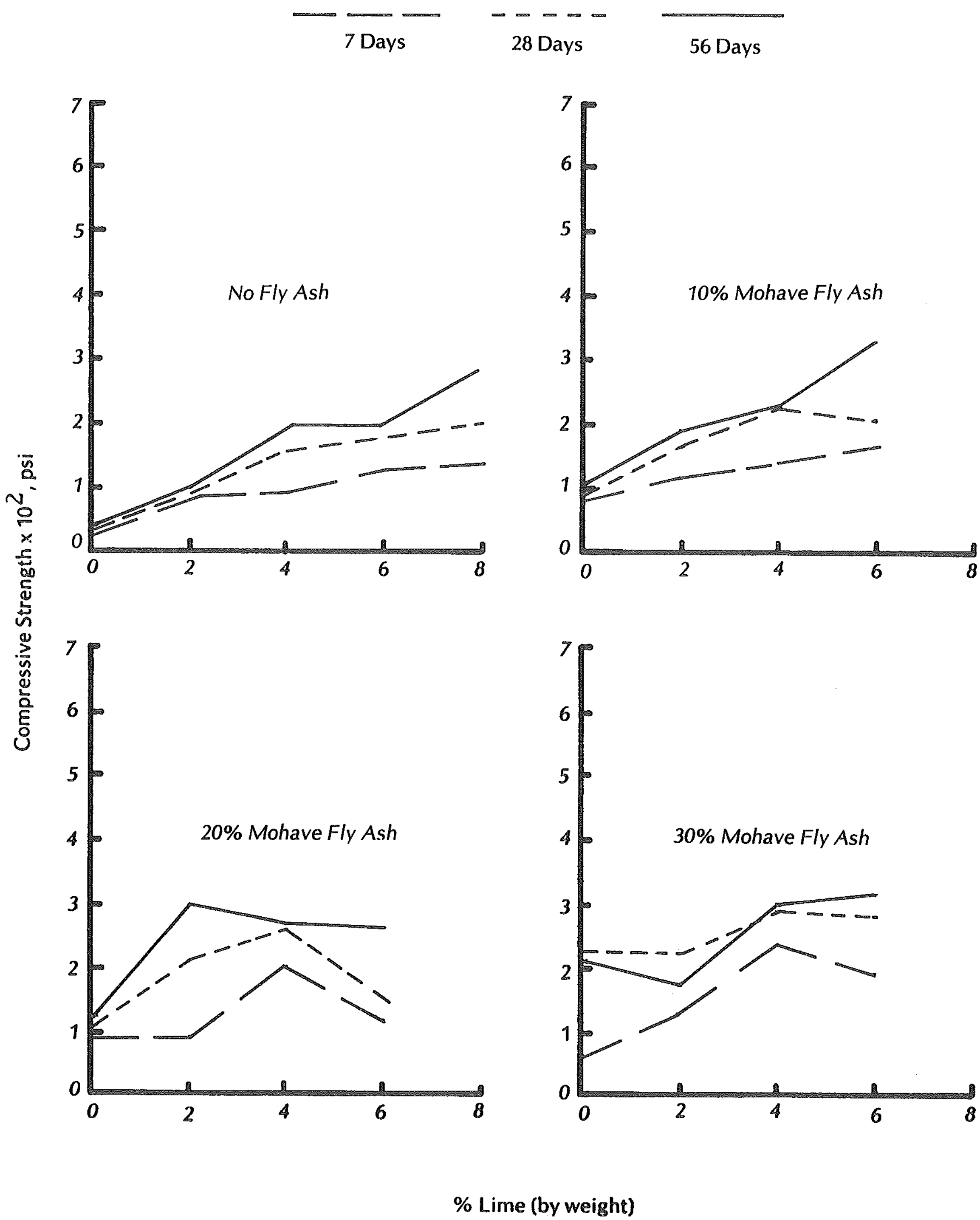


FIGURE 4-3C. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND MOHAVE FLY ASH.

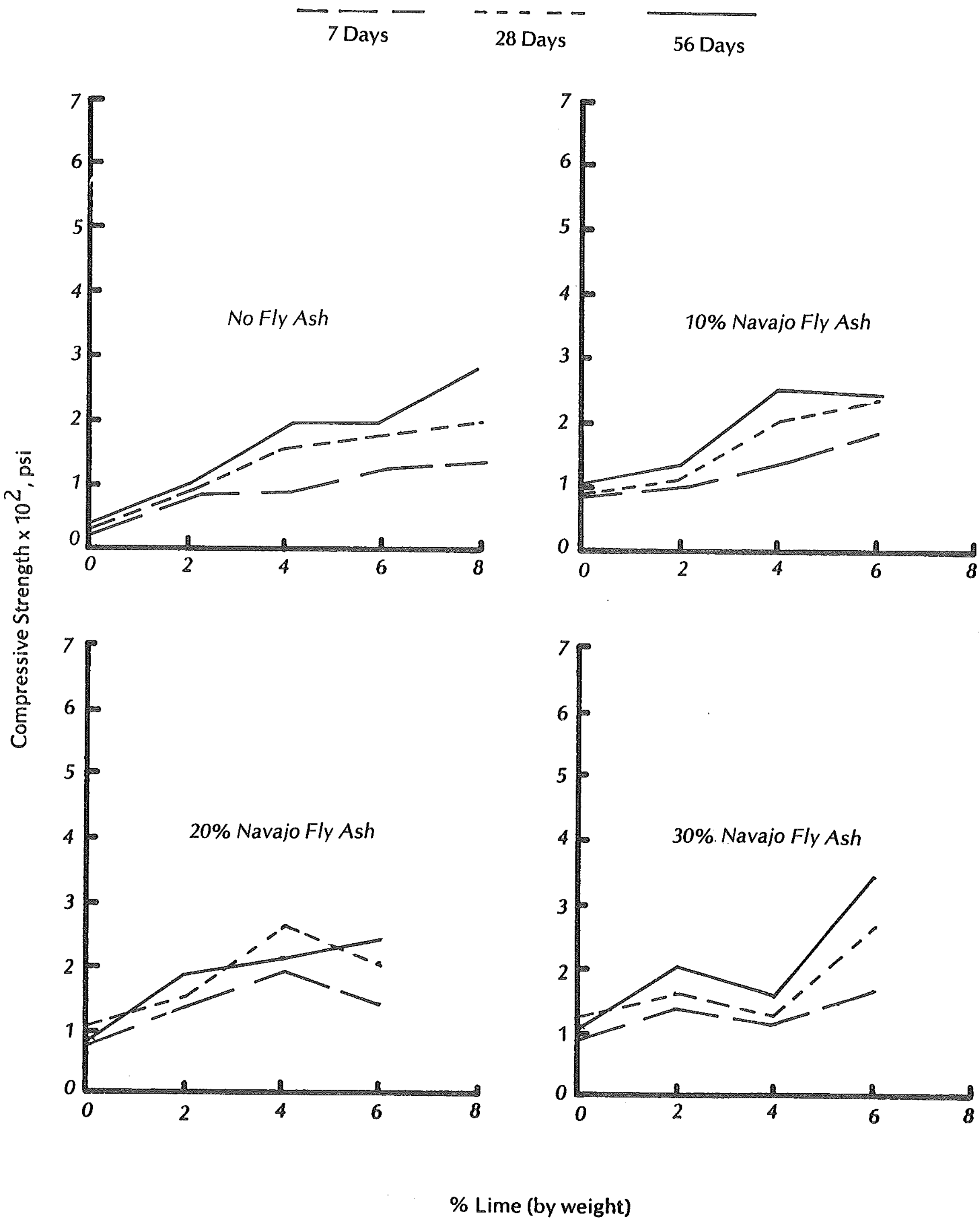


FIGURE 4-3D. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND NAVAJO FLY ASH.

Cholla	430 psi	(30 Kg/cm^2)	CH-6-C30-56
Four Corners	530 psi	(37 Kg/cm^2)	CH-6-F30-56
Mohave	320 psi	(23 Kg/cm^2)	CH-6-F10-56
Navajo	340 psi	(24 Kg/cm^2)	CH-6-N30-56
No Additive	40 psi	(3 Kg/cm^2)	CH-0- 0 -56

4.3.2.4 Cinders

The compressive strength vs. lime content test data for the cinder (GP) soil type are illustrated in Figure 4-4. Specimen geometry, as previously discussed, differed considerably from that of the other three soil types. Direct comparisons should only be made therefore, with due consideration for the differences in specimen sizes as well as the length-to-diameter ratios.

The cinder soil without additives did not have measurable unconfined compressive strength. The addition of fly ash, without lime, did not result in any measureable strength; however lime, alone, did result in the development of a low strength. Moderate strengths were achieved with 6% lime and 20% fly ash, the maximum for the series. Peak strengths for the single source of fly ash used (Cholla) were:

Cholla	320 psi	(23 Kg/cm^2)	GP-6-C20-56
No Additive	0 psi		GP-0- 0 -56

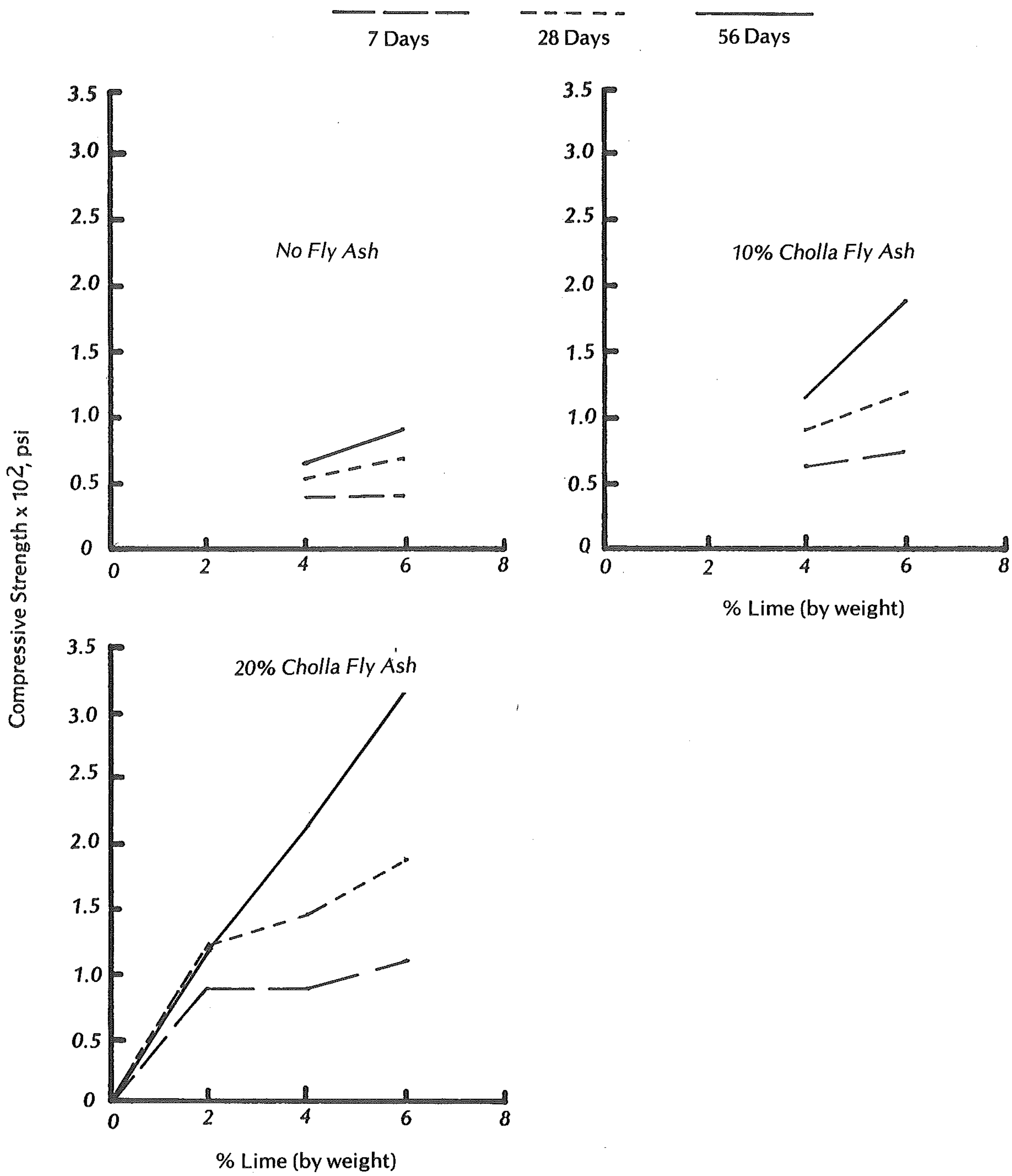


FIGURE 4-4. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CINDERS AND CHOLLA FLY ASH.

4.3.3 Unconfined Compressive Strength vs. Age

The discussion in the previous section generally dealt with the relationship between strength and lime content for various fly ash contents and ages. The direct relationship between strength gain and age is also of prime importance since the strength gain takes place over a relatively long period of time. Rates of strength gain are illustrated in the curves of Figures 4-5, 6, 7 and 8. The age-strength curves include all data developed in the study and included in Appendix B. Each soil type and fly ash source combination is presented separately with all tested proportions of lime and fly ash.

4.3.3.1 Clayey Sand

The clayey sand demonstrated similar performance when combined with the Cholla, Four Corners and Navajo fly ashes. Most combinations, including lime without fly ash, exhibited a continued significant strength gain up to the final test age of 56 days. The rate of strength gain appeared only slightly less from 28 to 56 days than from 7 to 28 days, and therefore indicated probable continued gain for some undetermined time. The exceptions to this were the specimens with no lime which, irrespective of fly ash content, did not gain strength with time.

The Mohave fly ash combinations behaved uniquely in that a moderate rate of strength gain occurred for specimens with no lime. This was observed for all fly ash proportions and was attributed to the fly ash since no strength gain was observed for the clayey sand soil alone.

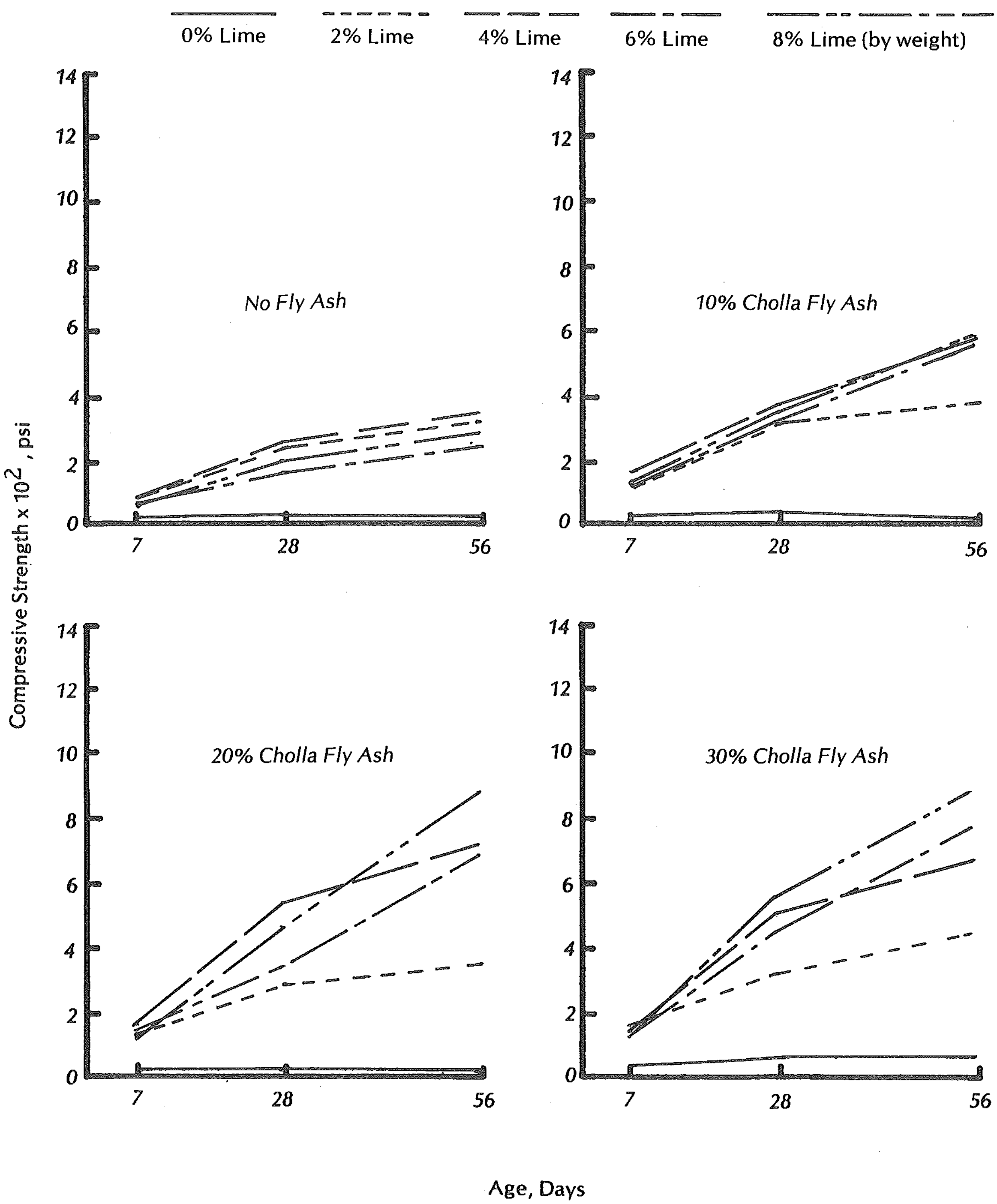


FIGURE 4-5A. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND CHOLLA FLY ASH.

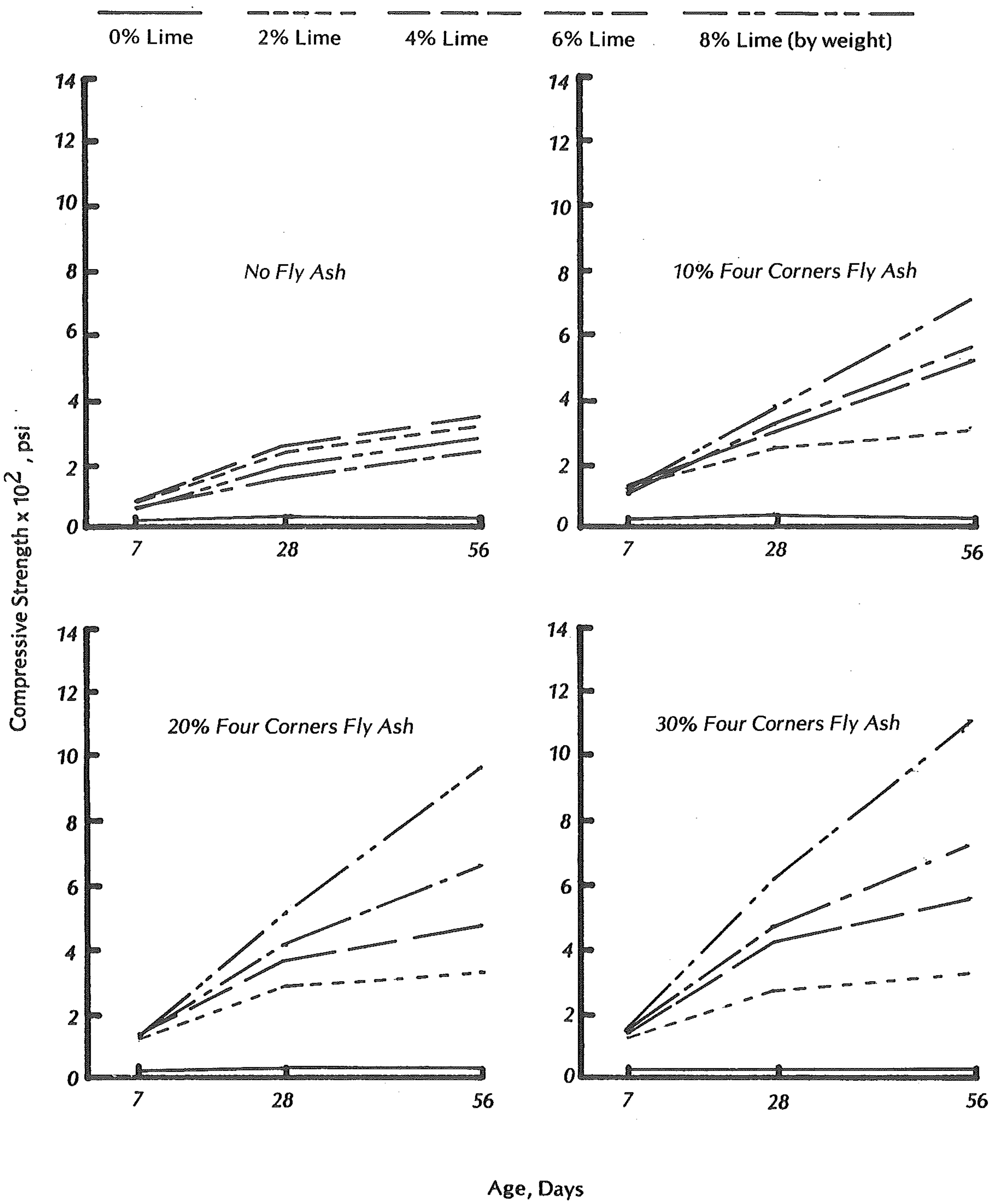


FIGURE 4-5B. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND FOUR CORNERS FLY ASH.

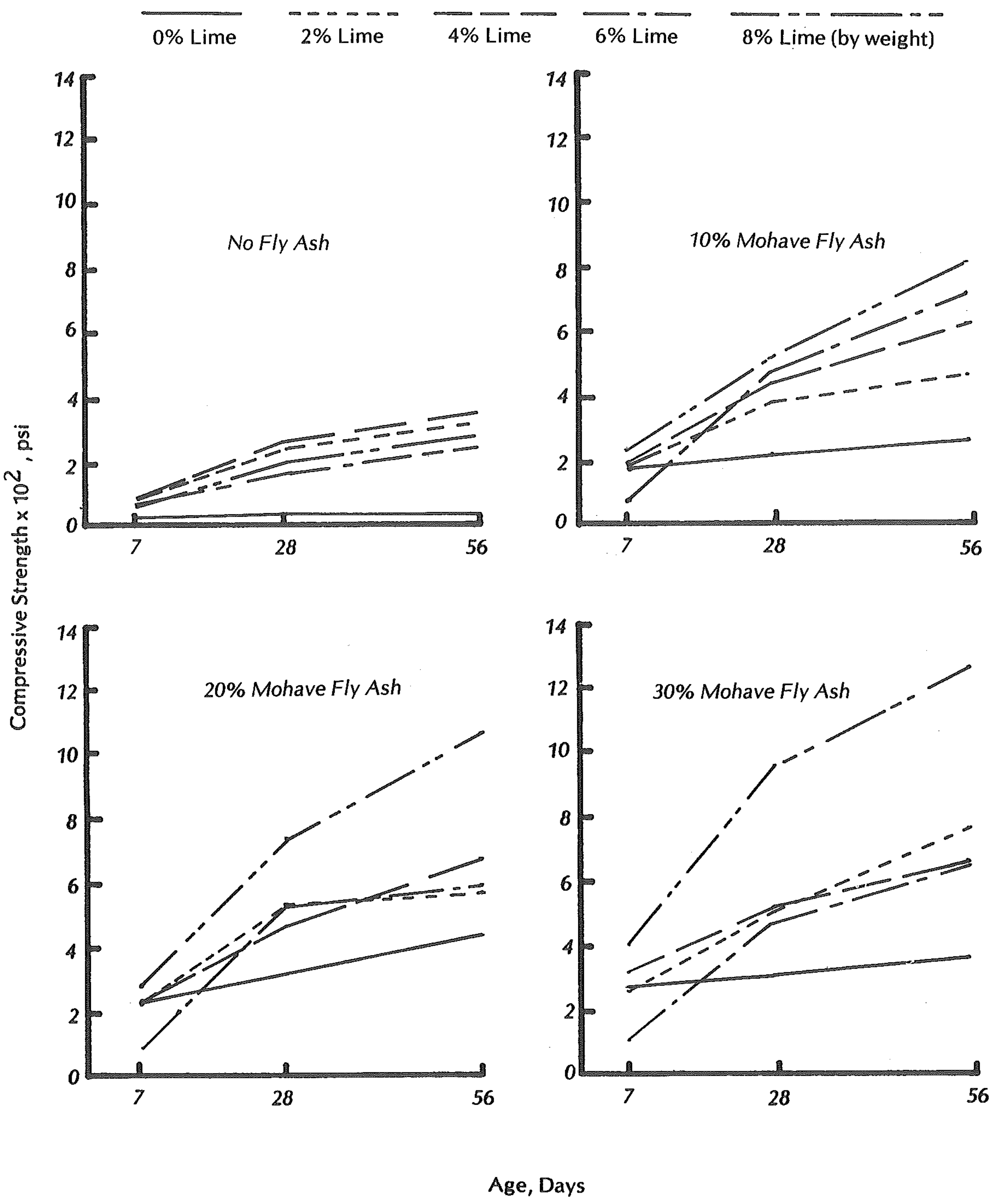


FIGURE 4-5C. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND MOHAVE FLY ASH.

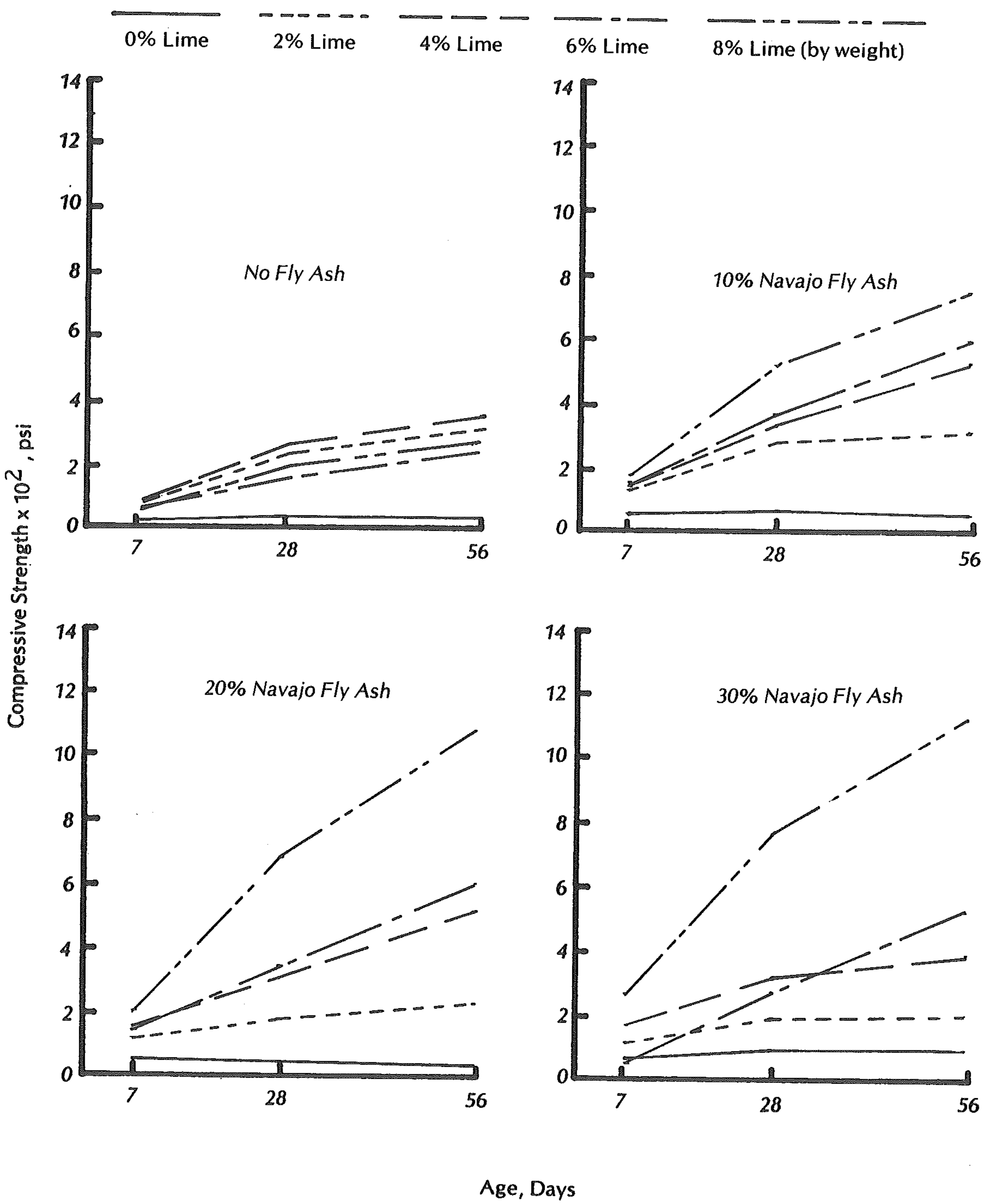


FIGURE 4-5D. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND NAVAJO FLY ASH.

4.3.3.2 Sand

Lime without fly ash did not result in strength gain with time for any combination tested. Fly ash alone resulted in a moderate rate of strength gain for the Mohave 30% series only.

The Cholla and Four Corners ash series showed similar rates of strength gain for all comparable combinations. Rates of strength increase remained nearly constant, for each mix combination, throughout the range of test ages. Combinations with high lime and fly ash proportions indicated probable significant strength gain beyond the final 56 day test age. Both the Mohave and Navajo series showed a general decrease in the rate of strength gain after 28 days, particularly for the higher lime proportions.

4.3.3.3 Clay

The rate of strength gain for the clay in combination with all fly ashes appeared to be strongly dominated by the lime content. The addition of fly ash alone resulted in moderate rates of strength gain for the Mohave fly ash series but no significant rates of increase for any other series. Several mix combinations, particularly in the Mohave and Navajo series and in the lower ranges of lime porportions showed no strength gain, or very slight strength gain, with time.

4.3.3.4 Cinders

The cinders test series was relatively limited compared to the other soil types. For most test series, the rate of strength gain was relatively uniform throughout the range of test ages, which indicated that significant continued gain in strength could be expected beyond the 56 day test age. A moderate rate of strength gain was noted for the lime-only series.

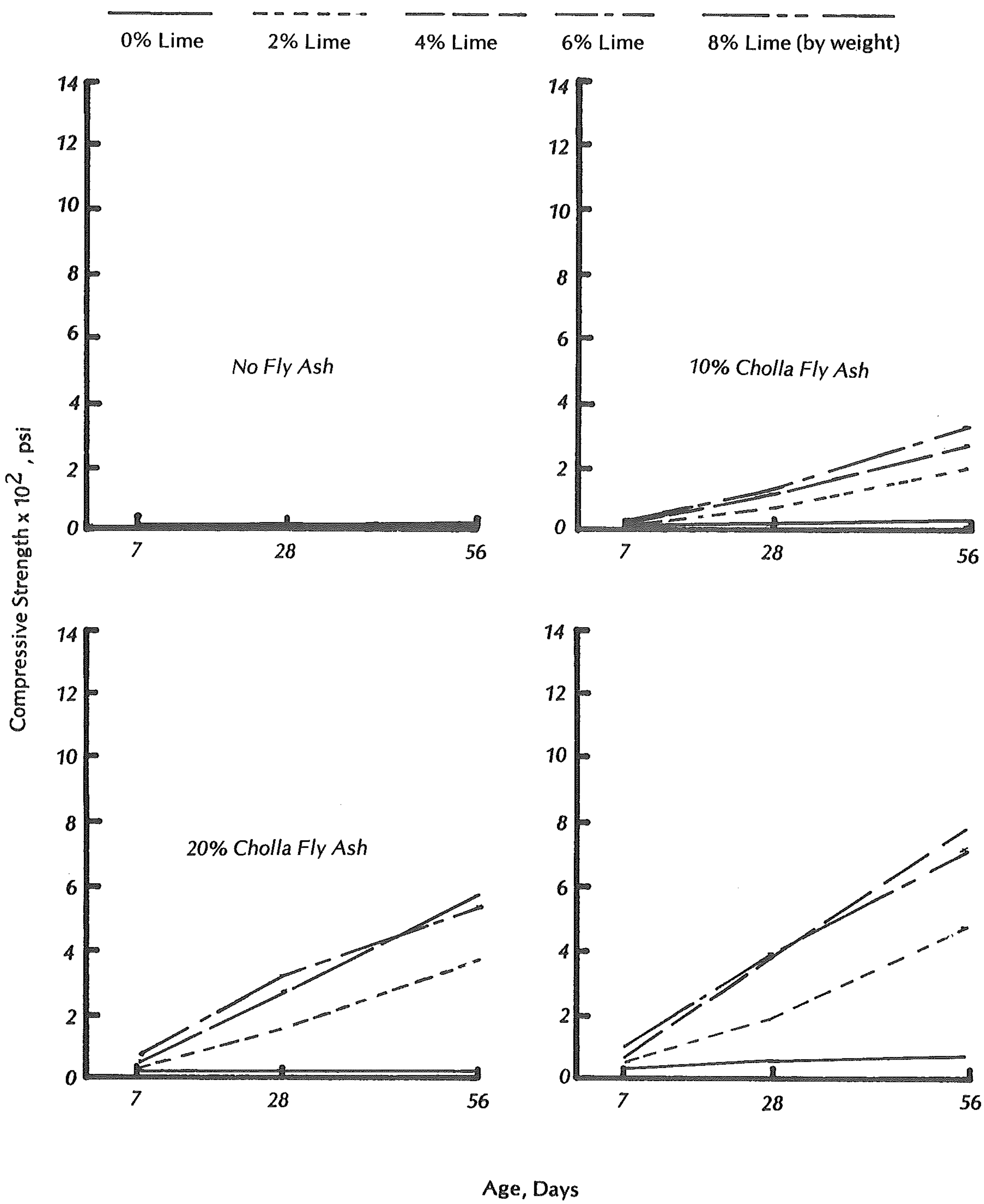


FIGURE 4-6A. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND CHOLLA FLY ASH.

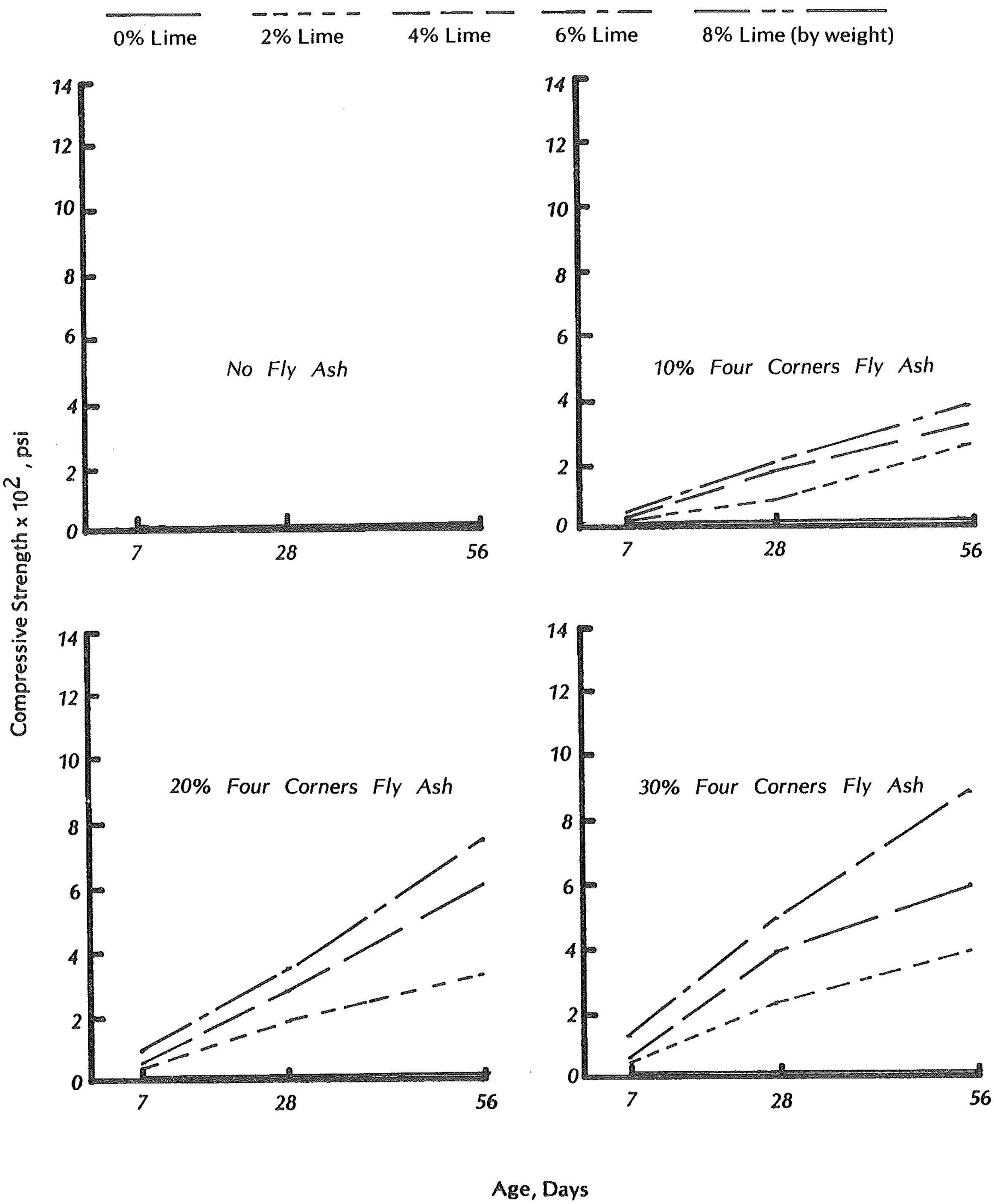


FIGURE 4-6B. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND FOUR CORNERS FLY ASH.

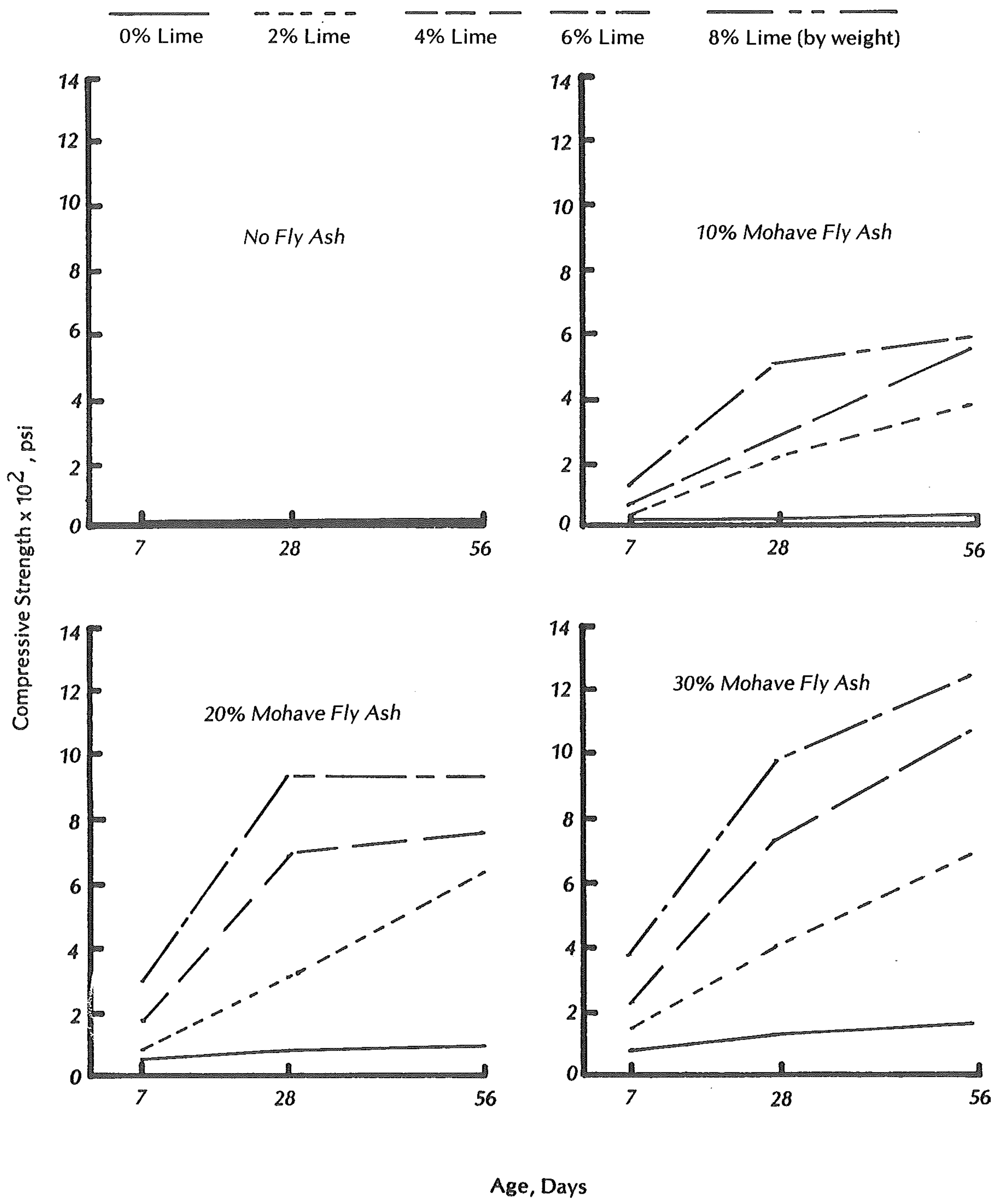


FIGURE 4-6C. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND MOHAVE FLY ASH.

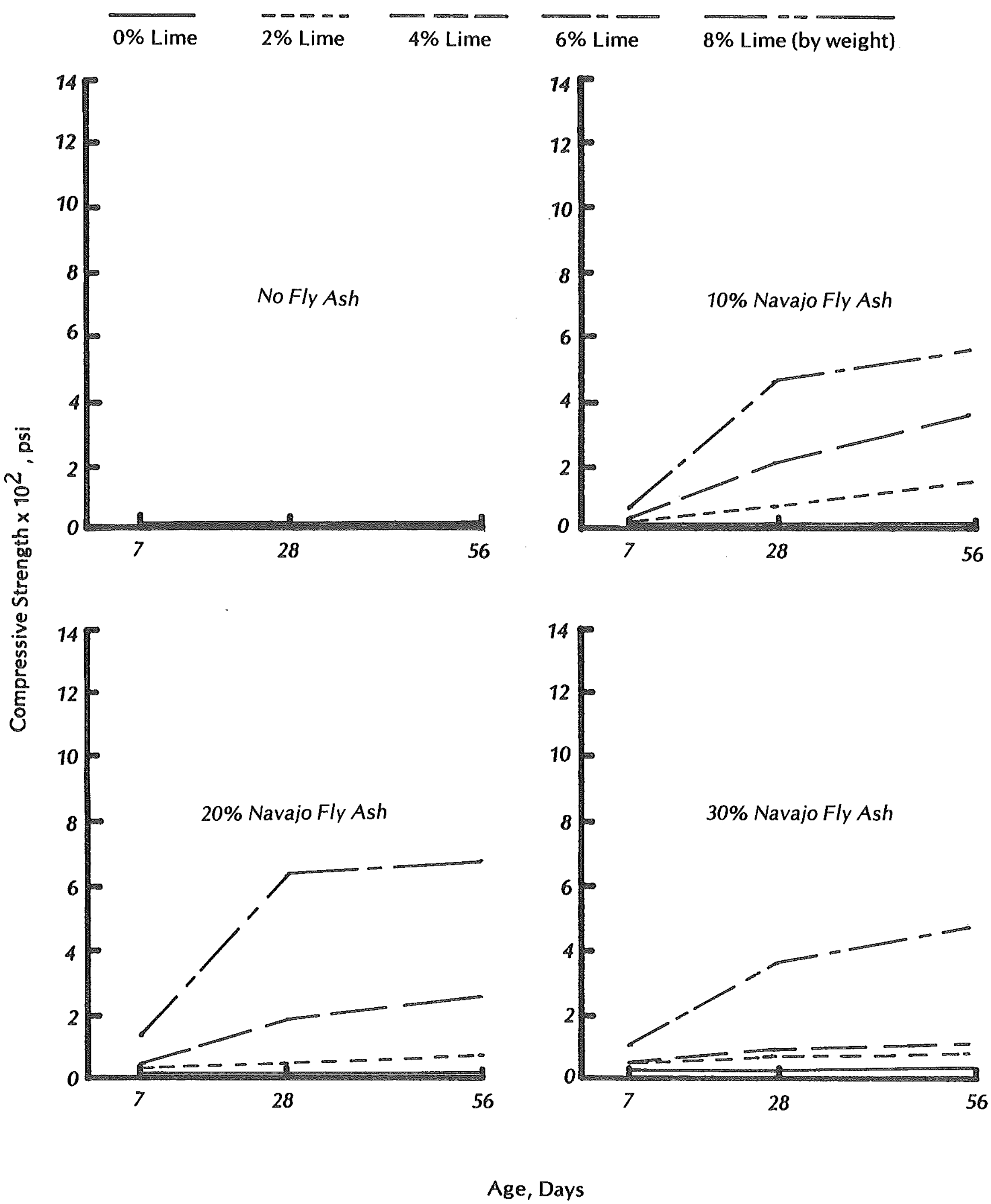


FIGURE 4-6D. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND NAVAJO FLY ASH.

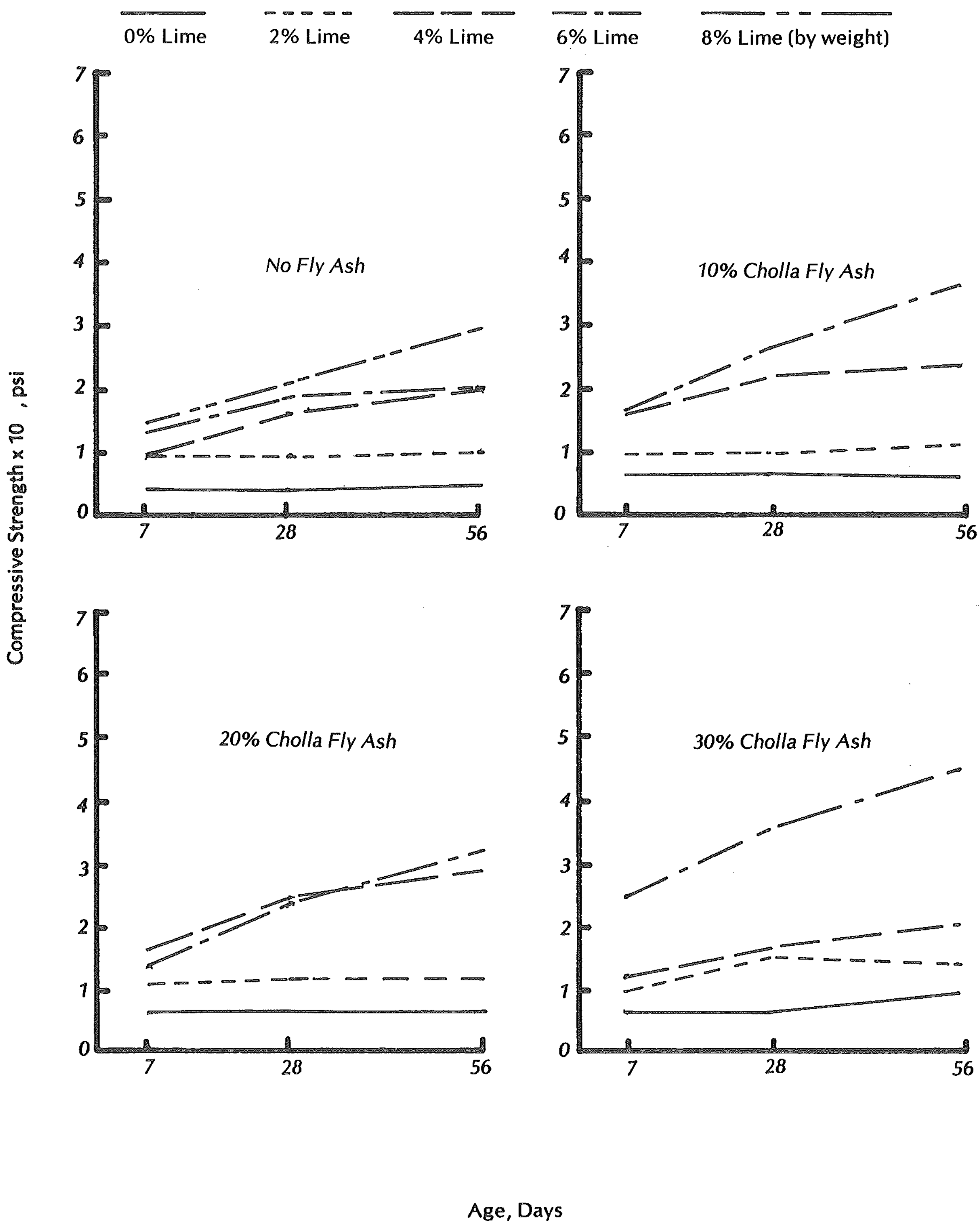


FIGURE 4-7A. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND CHOLLA FLY ASH.

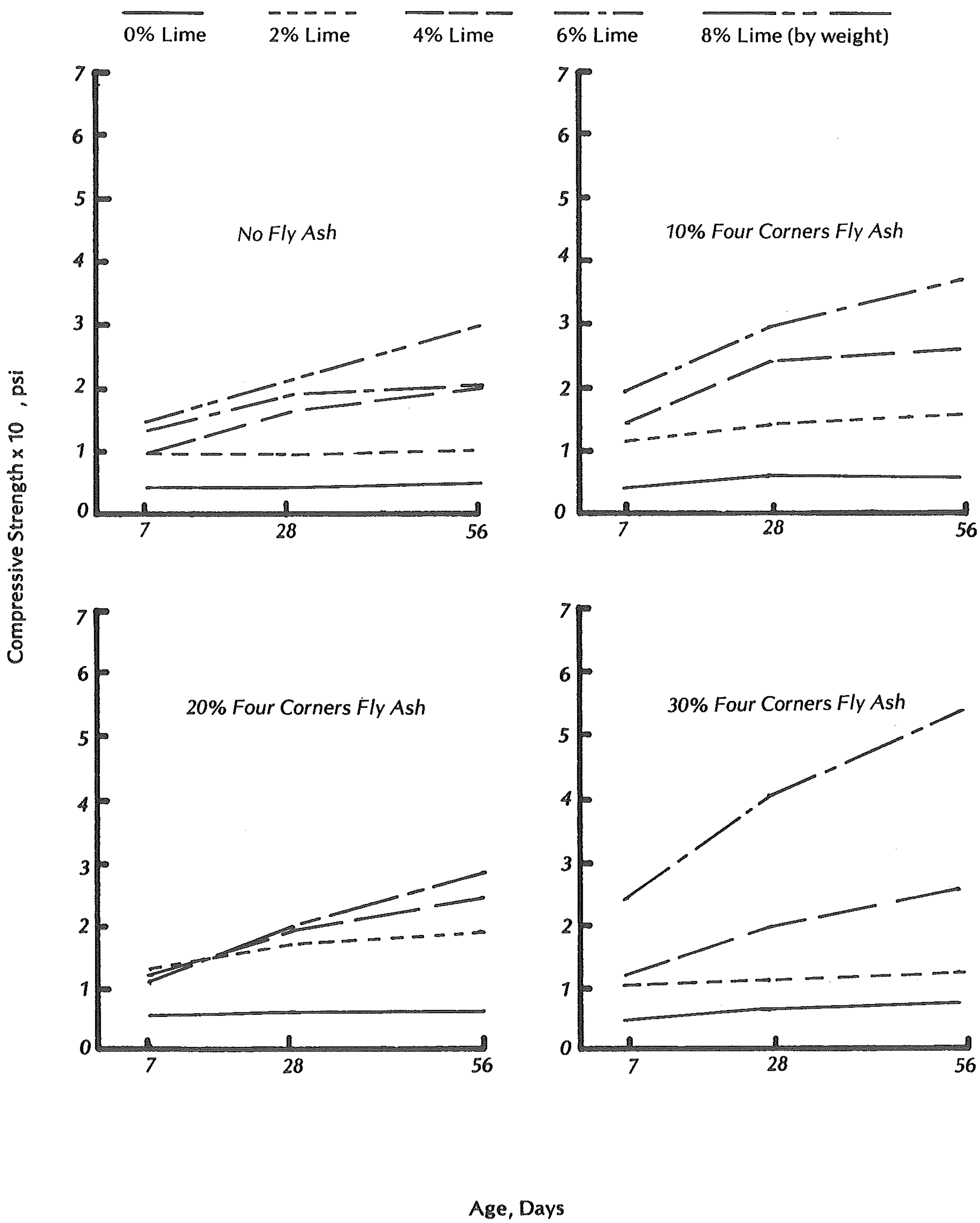


FIGURE 4-7B. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND FOUR CORNERS FLY ASH.

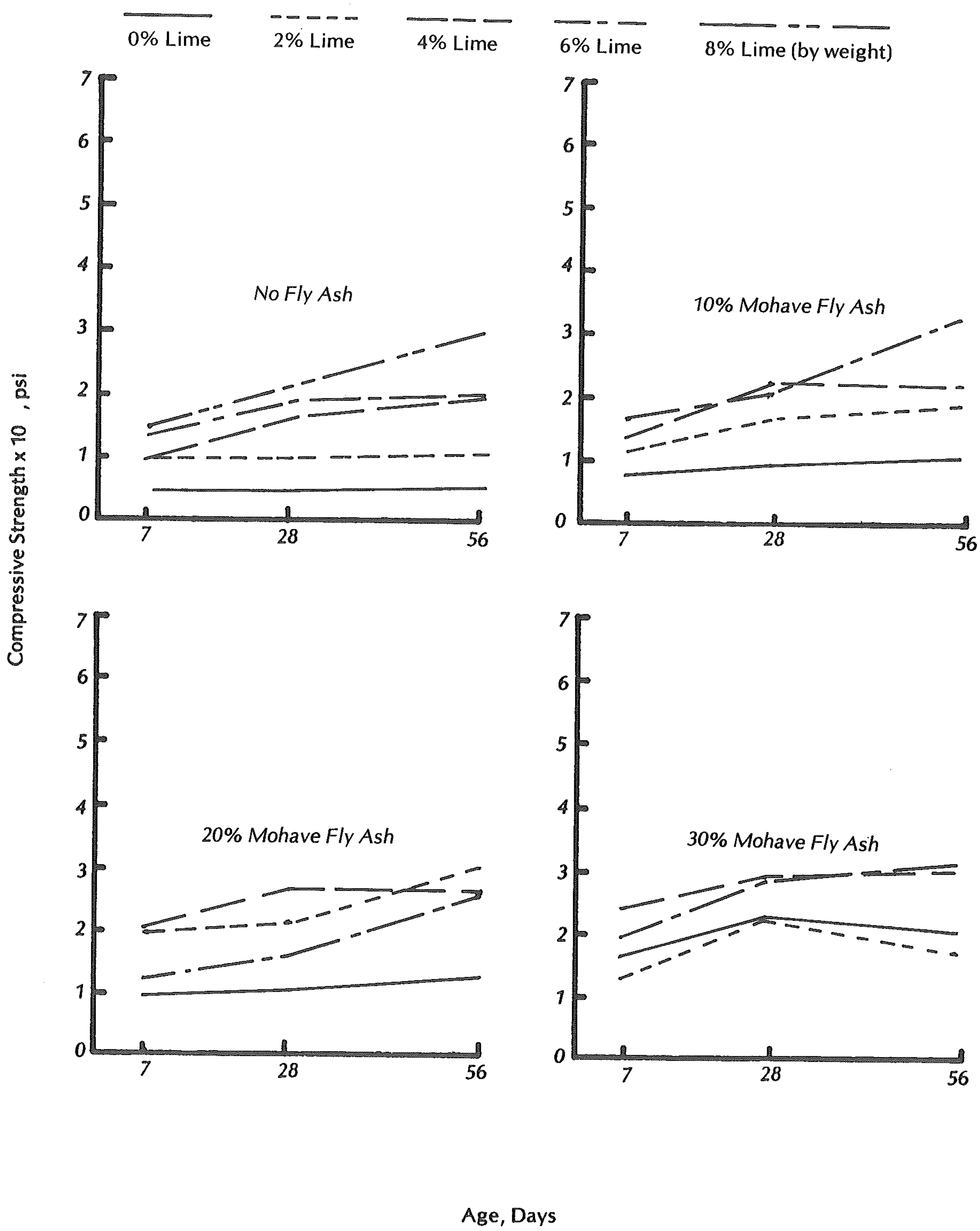


FIGURE 4-7C. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND MOHAVE FLY ASH.

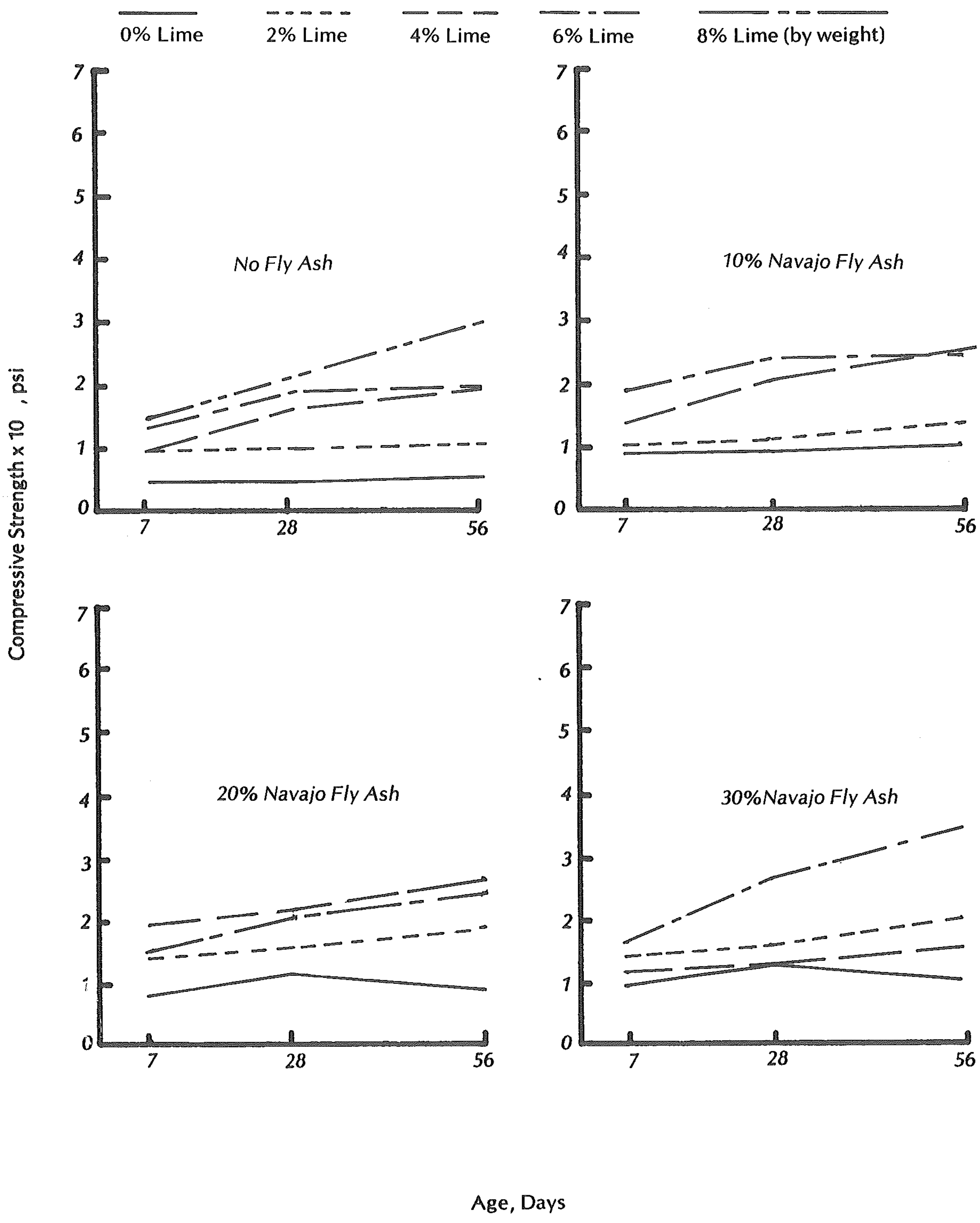


FIGURE 4-7D. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND NAVAJO FLY ASH.

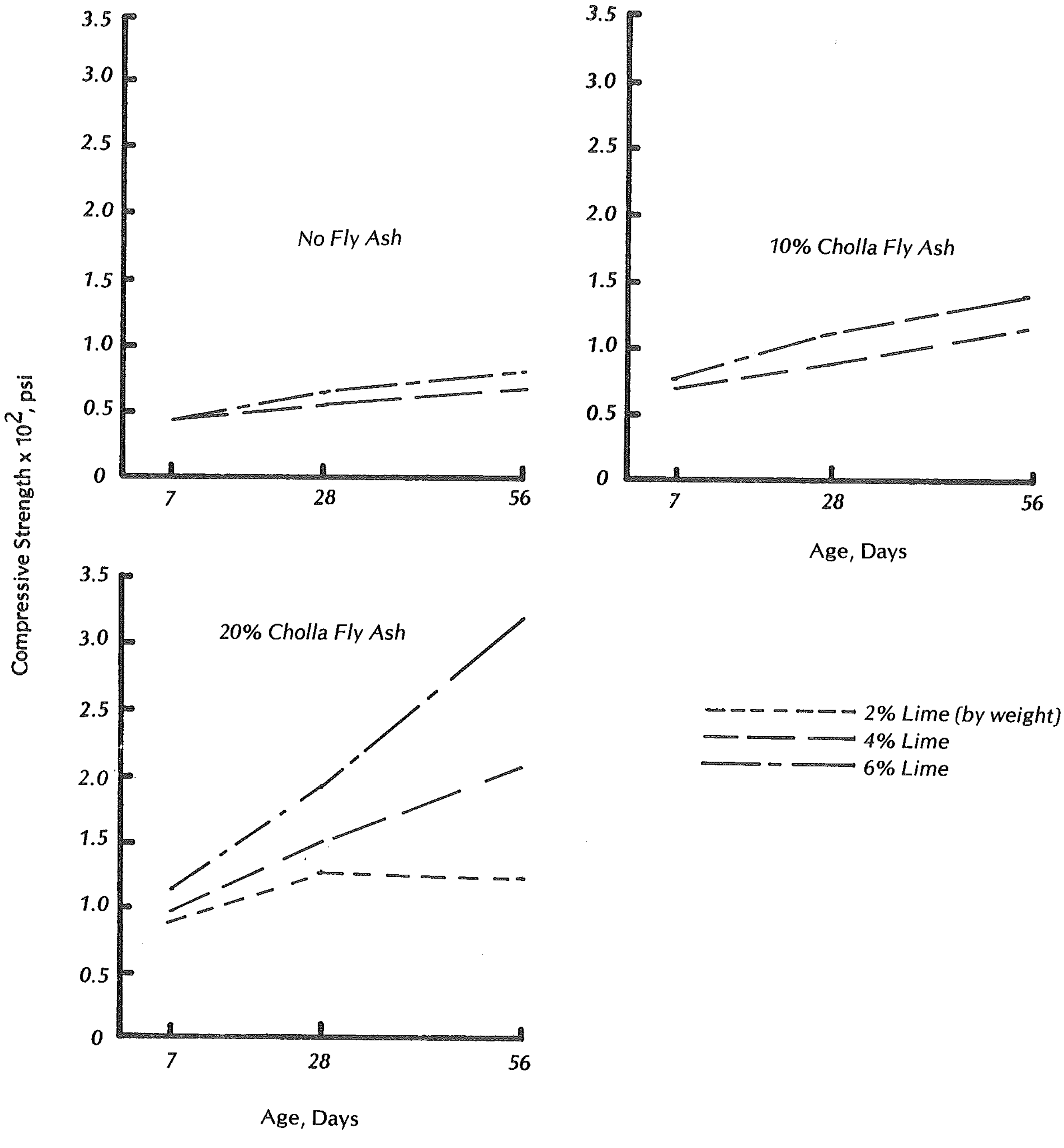


FIGURE 4-8. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CINDERS AND CHOLLA FLY ASH.

4.4 Data Uniformity and Reliability

4.4.1 General

Laboratory test data was evaluated in two areas to assess the general reliability and reproduceability of results. The range of variation within sets of companion specimens was evaluated to determine what specimens, if any, should be discarded as suspect. In addition, selected sets of companion specimens were duplicated for comparison with the originals.

4.4.2 Within-Test Variation

Several randomly selected sets of companion specimens were duplicated using sets of 10 specimens rather than the usual 3. Evaluation of these sets of 10 indicated that a coefficient of variation of about 15% was present in the test results. Based on judgement and the simple statistical evaluation of these small groups of observations, it was decided that test results which fell within $\pm$45% of the average for the set should be included in the average. This rule was applied in the determination of unconfined compressive strength for each set of companion specimens.

4.4.3 Duplication of Results

The data represented by the strength vs. time curves of Chapter 4 (Figures 4-5, 6, 7 and 8) indicated a number of outstanding deviations from the trends established by the data as a whole. Data points which appeared to deviate markedly from the established pattern were checked by preparing and testing duplicate sets of specimens. Such duplicate data were developed for 23 of the lime-soil-fly ash combinations in the clayey sand test series.

Strengths of the duplicate sets varied from 54% to 129% of those of the original sets. Approximately half of the retest sets resulted in no significant change in the apparent strength-time trends. Of the remaining sets, a few introduced new apparent anomalies in the relationships and the remainder tended to move the strength-time curves in the direction of the established patterns.

The retest data were used only for subjective evaluation of the overall data and were not otherwise incorporated into the study program.

CHAPTER 5. DURABILITY

5.1 General

The test series described in the previous sections were designed to establish basic strength relationships for various combinations of the four soils, four fly ashes and lime. Unconfined compressive strength data were intended as an indication of the potential for a given set of soil-lime-fly ash proportions and not necessarily as an indicator of field performance. The purpose of this chapter is to study certain weathering characteristics of the lime-fly ash stabilized soils in order to bring the evaluation one step closer to field performance.

Three test series were performed to evaluate durability, including standardized wet-dry and freeze-thaw cycles and the testing of soaked specimens in unconfined compression.

5.2 Wetting and Drying

5.2.1 Laboratory Procedures

Testing was performed in accordance with a modification of AASHO Designation: T135-70, Wetting-and-Drying Test of Compacted Soil-Cement Mixtures (ASTM Designation: D 559-57). The curing period was revised from 7 to 28 days, since the soil-lime-fly ash reactions were known to develop more slowly than the cement hydration anticipated in the standard procedure. Molding data, including unit weights and as-molded moisture contents, are tabulated in Appendix B. The standard soil-cement test procedure was selected as a logical starting point for evaluation of wet-dry durability. In addition to rating the resistance of the mixtures to deterioration from wetting and drying, a secondary objective was to evaluate the suitability of the standard soil cement procedure for use with lime-soil-fly ash mixtures.

5.2.2 Test Results

Laboratory results for all series tested are tabulated in Tables 5-1a, b, c and d. Data include cycles completed, maximum volume change, maximum moisture content and final weight loss.

The clayey sand test series involved 15 lime-soil-fly ash mixtures, including 3 fly ash sources, lime proportions from 2% to 8% and fly ash proportions from 0% to 20%. All sets of specimens survived the 12 cycles of wetting and drying established by the standard test procedure. Volume changes overall ranged from -3.0% to 0.9%, although the range was reduced to -0.5% to +0.9% for those sets of specimens with 4% lime or more (irrespective of fly ash content). Maximum moisture contents ranged from 1% to 5% above optimum with no particular trends evidenced. Final weight losses were in the range of about 3% to 25%, and generally with increased lime content. The Mohave ash specimens appeared to outperform the Cholla and Navajo specimens (no Four Corners ash was included) by a clear margin.

The sand test series involved 8 lime-soil-fly ash mixtures, and included lime contents from 2% to 6%, fly ash contents from 0% to 20% and the Cholla fly ash only. Specimens with lime only failed to complete the 12 test cycles; however, the number of cycles completed increased with lime content. All specimens with lime and fly ash completed the 12 cycles. Maximum volume changes were in the general range of -2.4% to +3.3%. Maximum moisture contents increased from 0% to 4% above optimum during the test series. Weight losses were severe, and only the higher lime and fly ash contents (SP-4-20, SP-6-10 and SP-6-20) survived with losses of 10% or less.

TABLE 5-1a. Wet-Dry Durability Characteristics, Clayey Sand.

Wet-Dry Characteristic	% Lime	0% Fly Ash	% Cholla Fly Ash		% Mohave Fly Ash		% Navajo Fly Ash	
			10	20	10	20	10	20
* Cycles Completed	2	***	12	***	12	***	12	***
	4	12	12	12	12	12	12	12
	6	12	***	12	***	12	***	12
	8	12	***	***	***	***	***	***
Maximum Volume Change, %	2	***	-3.0	***	0.9	***	-2.8	***
	4	0.7	0.2	-0.2	0.7	0.4	0.4	0.4
	6	0.4	***	-0.5	***	0.9	***	0.2
	8	0.9	***	***	***	***	***	***
Maximum Moisture Content, %	2	***	15.0	***	13.3	***	13.7	***
	4	13.2	14.5	15.9	14.5	14.8	14.6	15.5
	6	14.0	***	16.2	***	15.4	***	16.0
	8	14.7	***	***	***	***	***	***
Final Weight Loss, %	2	**	25.1	***	14.8	***	18.5	***
	4	9.1	15.8	8.1	3.9	3.4	8.9	15.7
	6	3.6	***	4.7	***	3.3	***	5.9
	8	3.2	***	***	***	***	***	***

* In cases where the cycles completed are less than 12, the wet-dry characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-1b. Wet-Dry Durability Characteristics, Sand.

Wet-Dry Character-istics	% Lime	0% Fly Ash	% Cholla Fly Ash	
			10	20
* Cycles Completed	2	2	12	***
	4	7	12	12
	6	8	12	12
Maximum Volume Change, %	2	**	-1.2	***
	4	3.3	-2.4	1.5
	6	1.4	0.9	1.2
Maximum Moisture Content, %	2	12.0	13.2	***
	4	11.4	13.0	12.2
	6	11.3	12.2	12.5
Final Weight Loss, %	2	**	44.6	***
	4	68.6	21.8	10.1
	6	54.1	6.5	4.5

* In cases where the cycles completed are less than 12, the wet-dry characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-1c. Wet-Dry Durability Characteristics, Clay.

Wet-Dry Characteristics	% Lime	0% Fly Ash	% Cholla Fly Ash		% Mohave Fly Ash		% Navajo Fly Ash	
			10	20	10	20	10	20
* Cycles Completed	2	1	1	***	2	***	1	***
	4	1	2	1	2	2	1	1
	6	1	4	3	3	2	2	3
Maximum Volume Change, %	2	6.7	**	***	13.8	***	5.1	***
	4	12.9	-11.3	2.4	-3.3	2.2	4.2	4.1
	6	2.4	-7.2	-12.9	-6.9	2.4	0.9	2.4
Maximum Moisture Content, %	2	21.1	30.3	***	29.0	***	30.0	***
	4	26.7	26.0	25.4	25.6	25.7	28.0	28.6
	6	27.1	24.4	25.8	24.6	28.0	24.9	25.4
Final Weight Loss, %	2	**	**	***	39.9	***	19.2	***
	4	**	24.5	**	13.4	20.4	5.2	8.0
	6	**	19.0	28.6	18.8	22.0	11.4	16.0

* In cases where the cycles completed are less than 12, the wet-dry characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-1d. Wet-Dry Durability Characteristics, Cinders.

Wet-Dry Characteristics	% Lime	0% Fly Ash	% Cholla Fly Ash	
			10	20
* Cycles Completed	0	***	***	0
	2	***	***	1
	4	***	***	2
	6	2	2	12
Maximum Volume Change, %	0	***	***	**
	2	***	***	-1.9
	4	***	***	-2.7
	6	-4.0	0.6	-1.0
Maximum Moisture Content, %	0	***	***	**
	2	***	***	30.2
	4	***	***	28.0
	6	35.7	30.3	28.4
Final Weight Loss, %	0	***	***	**
	2	***	***	**
	4	***	***	11.1
	6	43.7	21.3	50.8

* In cases where the cycles completed are less than 12, the wet-dry characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

Eighteen mixtures were tested in the clay soil series including lime contents from 2% to 6%, fly ash contents from 0% to 20% and 3 fly ashes (Cholla, Mohave and Navajo). No specimens survived more than 4 cycles of the scheduled 12. The number of cycles completed appeared to increase with lime content, irrespective of fly ash content or source. Volume changes were relatively high, in the general range of -13% to +14%. The maximum increase in moisture content varied from about 0% to 11% above optimum during the tests. Moisture change appeared to increase with higher fly ash contents and decrease with higher lime contents. Both volume changes and moisture changes should be considered as estimates since specimens deteriorated too rapidly for reliable weights and measurements to be obtained. Weight losses were high and in some cases the control sample deteriorated more rapidly than the brushed sample. The few low values of weight loss were misleading since companion samples had deteriorated so badly they could no longer be handled. The weight loss criteria did not provide any basis for ranking the mixtures since completed cycles varied and weight losses were erratic and misleading.

The cinder test series was performed using only the Cholla fly ash and with lime and fly ash contents in the ranges of 0% to 6% and 0% to 20% respectively. Of the 6 mixtures tested, only one (GP-6-20) survived the standard 12 test cycles. The remaining series failed in from 0 to 2 cycles. Indicated volume changes were in the range of -4% to +1% and moisture changes appeared to be negligible. Both volume and moisture observations were estimated since most specimens deteriorated too rapidly for accurate weight and measurements to be obtained. Weight loss for the single specimen to survive

12 cycles was 50%. Indicated weight loss for the remainder of the specimens was less than 50% although the values are not comparable due to great differences in completed cycles.

5.3 Freezing and Thawing

5.3.1 Laboratory Procedures

Freeze-thaw testing was performed in accordance with a modification of AASHO Designation: T136-70 (ASTM Designation: D560-57). The curing period was revised from 7 days to 28 days, since the soil-lime-fly ash reactions were known to develop more slowly than the cement hydration anticipated in the standard procedure. Molding data, including unit weight and as-molded moisture contents are tabulated in Appendix B. The standard soil-cement test procedure was selected as a logical starting point for evaluation of freeze-thaw durability. In addition to rating the resistance of the specimen to deterioration from freezing and thawing, a secondary objective was to evaluate the suitability of the standard soil cement procedure for use with lime-soil-fly ash mixtures.

5.3.2 Test Results

Laboratory results for all series tested are tabulated in Tables 5-2a, b, c and d. Data include cycles completed, maximum volume change, and final weight loss.

The clayey sand test series involved 15 lime-soil-fly ash mixtures, and included 3 fly ash sources, lime proportions from 2% to 8% and fly ash proportions from 0% to 20%. All sets of specimens survived the 12 freeze-thaw cycles established by the standard test procedure. Volume changes were erratic and difficult to evaluate

TABLE 5-2a. Freeze-Thaw Durability Characteristics, Clayey Sand

Freeze-Thaw Characteristic	% Lime	0% Fly Ash	%Cholla Fly Ash		%Mohave Fly Ash		%Navajo Fly Ash	
			10	20	10	20	10	20
* Cycles Completed	2	***	12	***	12	***	12	***
	4	12	12	12	12	12	12	12
	6	12	***	12	***	12	***	12
	8	12	***	***	***	***	***	***
Maximum Volume Change, %	2	***	4.9	***	5.9	***	9.8	***
	4	6.6	7.5	8.3	10.1	-12.1	15.5	18.7
	6	10.7	***	10.1	***	-10.1	***	12.8
	8	21.9	***	***	***	***	***	***
Final Weight Loss, %	2	***	33.0	***	20.7	***	37.5	***
	4	32.3	27.4	35.5	24.2	23.5	37.2	55.5
	6	40.5	***	31.9	***	20.6	***	52.1
	8	51.6	***	***	***	***	***	***

* In cases where the cycles completed are less than 12, the freeze-thaw characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

*** Combination not tested.

TABLE 5-2b. Freeze-Thaw Durability Characteristics, Sand

Freeze-Thaw Characteristics	% Lime	0% Fly Ash	%Cholla Fly Ash 10	%Cholla Fly Ash 20
* Cycles Completed	2	1	12	***
	4	1	12	12
	6	1	12	12
Maximum Volume Change, %	2	2.2	-2.5	***
	4	0.7	8.2	8.3
	6	4.3	3.7	-7.3
Final Weight Loss, %	2	**	64.0	***
	4	**	59.8	36.0
	6	**	60.8	37.6

* In cases where the cycles completed are less than 12, the freeze-thaw characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-2c. Freeze-Thaw Durability Characteristics, Clay

Freeze-Thaw Characteristic	% Lime	0% Fly Ash	%Cholla Fly Ash		%Mohave Fly Ash		%Navajo Fly Ash	
			10	20	10	20	10	20
* Cycles Completed	2	1	0	***	3	***	0	***
	4	1	5	3	3	6	2	4
	6	5	8	8	8	7	7	7
Maximum Volume Change, %	2	7.6	**	***	9.5	***	3.7	***
	4	6.3	10.8	7.8	8.8	11.6	5.3	2.8
	6	7.9	12.6	11.8	10.5	23.5	12.1	26.4
Final Weight Loss, %	2	**	**	***	**	***	**	***
	4	**	**	**	**	40.6	**	**
	6	**	42.9	54.3	36.8	46.6	52.7	59.5

* In cases where the cycles completed are less than 12, the freeze-thaw characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-2d. Freeze-Thaw Durability Characteristics, Cinders

Freeze-Thaw Characteristic	% Lime	0% Fly Ash	%Cholla Fly Ash 10	%Cholla Fly Ash 20
* Cycles Completed	0	***	***	1
	2	***	***	1
	4	***	***	7
	6	2	3	5
Maximum Volume Change, %	0	***	***	2.0
	2	***	***	3.3
	4	***	***	-2.3
	6	-2.3	1.6	3.5
Final Weight Loss, %	0	***	***	**
	2	***	***	**
	4	***	***	57.3
	6	39.2	50.4	45.9

* In cases where the cycles completed are less than 12, the freeze-thaw characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

due to weight losses and consequent dimensional changes which occurred in the control specimens. Maximum volume change data, tabulated in Table 5-2a was therefore not considered reliable or indicative. Weight losses were high, and varied from about 21% to 56%. Variations in weight loss nevertheless appeared to provide a clear correlation between durability and fly ash source. Ranked from most durable to least durable, Mohave, Cholla and Navajo fly ash specimens compared in that order for each comparable series.

The sand test series involved 8 lime-soil-fly ash mixtures and included lime contents from 2% to 6%, fly ash contents from 0% to 20% and the Cholla fly ash only. Specimens with lime only (no fly ash) deteriorated to failure within the first freeze-thaw cycle. All specimens with lime and fly ash completed the 12 standard cycles. Maximum volume changes could only be estimated due to spalling which rendered accurate measurement impossible. Weight losses were very high, 36% to 64%, at completion of the 12 cycles. The higher lime and fly ash contents suffered the lower weight losses (SP-4-20C and SP-6-20C).

Eighteen mixtures were tested in the clay soil series, including lime contents from 2% to 6%, fly ash contents from 0% to 20% and 3 fly ashes (Cholla, Mohave and Navajo). No mixture completed the standard 12 cycles. The number of cycles completed varied from 0 for two of the low lime mixtures to a high of 8 for three of the high lime mixtures. Cycles completed increased with lime content and with the addition of fly ash. Volume changes were again only estimated due to spalling of the control specimens. Weight losses were very high, 37% to 60%, in specimens which remained in suitable condition for weight determination. In general only the high (6%) lime specimens could be weighed. Based on weight loss, the Mohave ash specimens deteriorated slightly less than the Cholla and Navajo specimens.

The cinder test series was performed using only the Cholla fly ash and with lime and fly ash contents in the ranges of 0% to 6% and 0% to 20% respectively. None of the mixtures survived the 12 standard test cycles. The highest number of cycles completed by the 6 mixtures was 7 cycles for the GP-6-20C mix. Volume changes were inconclusive due to deterioration of control specimens. Weight losses were very high, 39% to 57%, with no trends indicated.

5.4 Soaked Compressive Strength

5.4.1 Laboratory Procedures

Thirteen sets of specimens in the clayey sand soil series were tested in soaked unconfined compressive strength. Soil-lime-fly ash mixtures were selected to represent the Cholla and Navajo fly ash, lime contents of 2% to 6%, fly ash contents of 10% to 30% and curing periods of 28 and 56 days. Specimens were molded along with the regular unconfined compressive strength samples. Molding densities and moisture contents are therefore represented by the data in the appropriate categories of Appendix B.

Except for the 24 hours immediately preceding testing, specimens were cured in the same manner as specimens to be tested at molding (optimum) water content. Specimens were soaked in distilled water at moist room temperature for the 24 hours prior to testing.

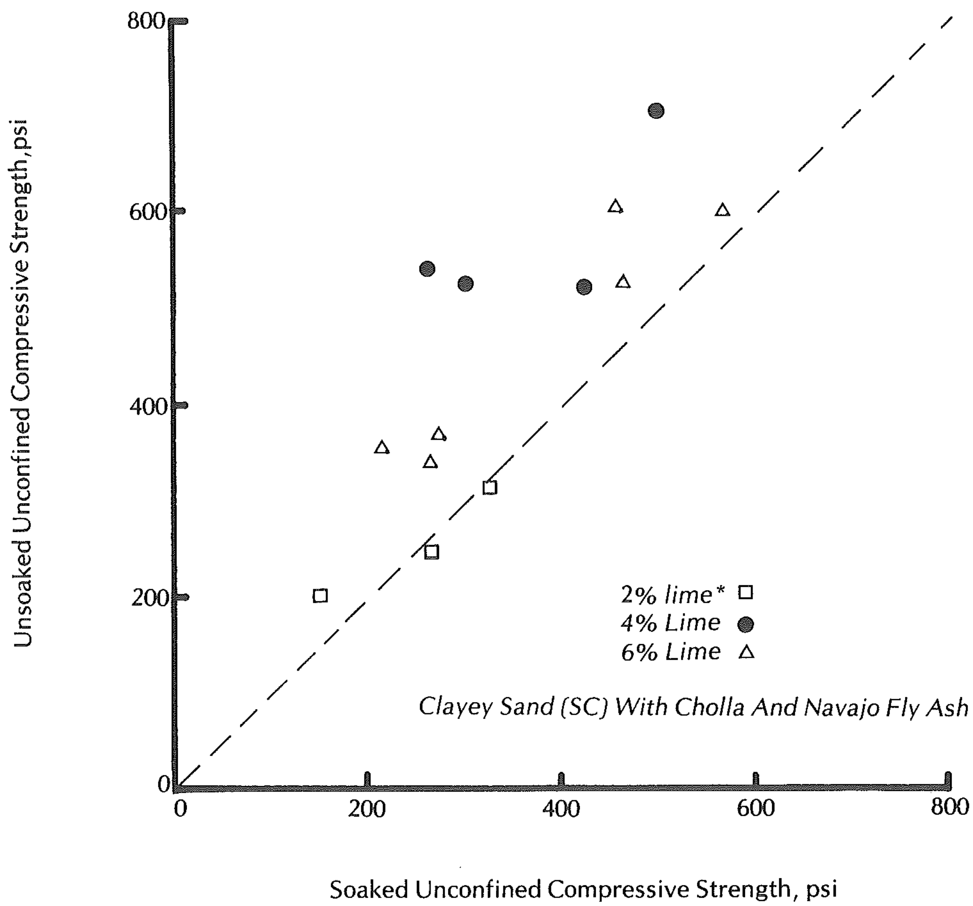
After curing and soaking, specimens were tested in unconfined compression as previously described in Chapter 4.

5.4.2 Test Results

Unconfined compressive strengths of soaked specimens were compared to the strengths of companion specimens tested at molding water content. Expressed as a percentage of the strength of the unsoaked specimens, the strengths ranged from 48% to 107% with a median value of 77% and an average of 79%. The comparison between comparable soaked and unsoaked strengths is illustrated in Figure 5-1.

Ranked in order of per cent retained strength, the data indicated that age was the significant factor in maintaining a high retained strength. All 28 day specimens ranked at or below the average strength, as can be seen in Table 5-3. Lime and fly ash contents did not appear to correlate well with retained strength. Absolute values of compressive strengths also provided little clear indication of potential retained strength; higher compressive strengths (at optimum moisture) tended toward lower retained strengths.

Soaked compressive strength data are included in Appendix B. Each tabulated value is an average for 3 companion specimens.



*By Weight

FIGURE 5-1. SOAKED VS. UNSOAKED UNCONFINED COMPRESSIVE STRENGTH

TABLE 5-3. Unconfined Compressive Strength Retained after 24 Hour Soak, Clayey Sand

% Lime	Fly Ash Source	% Fly Ash	Cure, Days	Unconfined Compressive Strength		
				Unsoaked, psi	Soaked, psi	Soaked/Unsoaked, %
2	Navajo	20	56	242	260	107
2	Navajo	10	56	312	321	103
6	Navajo	10	56	594	574	97
6	Navajo	30	56	534	467	87
4	Navajo	10	56	521	426	82
6	Cholla	20	28	339	269	79
6	Navajo	10	28	363	281	77
6	Navajo	20	56	601	463	77
2	Navajo	20	28	195	146	75
6	Navajo	20	28	353	225	72
4	Cholla	20	56	705	497	70
4	Navajo	20	56	522	299	57
4	Cholla	20	28	538	259	48